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Field Testing and Adaptation of a Methodology to Measure 'In-Stream' Values in the Tongue River, Northern Great Plains (NGP) Region

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A comprehensive, multi-component in-stream flow methodology was developed and field tested in the Tongue River in southeastern Montana. The methodology incorporates a sensitivity for the flow requirements of a wide variety of in-stream uses, and the flexibility to accommodate seasonal and subseasonal changes in the flow requirements for different uses. In-stream flow requirements were determined by additive independent methodologies developed for: 1) fisheries, including spawning, rearing and food production; 2) sediment transport; 3) mitigation of adverse impacts of ice; and 4) evapotranspiration losses. Consideration of a single in-stream flow requirement is inadequate since flow requirements for each use varied throughout the year. The methodology can be an effective water management tool.

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FIELD TESTING AND ADAPTATION OF A METHODOLOGY TO MEASURE "IN-STREAM" VALUES IN THE TONGUE RIVER, NORTHERN GREAT PLAINS (NGP) REGION

by

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for the

U. S. Environmental Protection Agency
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ABSTRACT

A comprehensive, multi-component in-stream flow methodology was developed and field tested in the Tongue River in southeastern Montana. The methodology incorporates a sensitivity for the flow requirements of a wide variety of in-stream uses, and the flexibility to adjust flows to accommodate seasonal and sub-seasonal changes in the flow requirements for different uses. In addition, the methodology provides the means to accurately determine the magnitude of the water requirement for each in-stream use. The methodology can be a powerful water management tool in that it provides the flexibility and accuracy necessary in water use negotiations and evaluation of trade-offs.

In contrast to most traditional methodologies, in-stream flow requirements were determined by additive independent methodologies developed for: 1) fisheries, including spawning, rearing, and food production; 2) sediment transport; 3) the mitigation of adverse impacts of ice; and 4) evapotranspiration losses. Since each flow requirement varied in importance throughout the year, the consideration of a single in-stream use as a basis for a flow recommendation is inadequate.

The study shows that the base flow requirement for spawning shovelnose sturgeon was 13.0 m^3/sec. During the same period of the year, the flow required to initiate the scour of sediment from pools is 18.0 m^3/sec., with increased scour efficiency occurring at flows between 20.0 and 25.0 m^3/sec.

An over-winter flow of 2.83 m^3/sec. would result in the loss of approximately 80% of the riffle areas to encroachment by surface ice. At the base flow for insect production, approximately 60% of the riffle

area is lost to ice. Serious damage to the channel could be incurred from ice jams during the spring break-up period. A flow of 12.0 m^3/sec. is recommended to alleviate this problem. Extensive ice jams would be expected at the base rearing and food production levels.

The base rearing flow may be profoundly influenced by the loss of streamflow to transpiration. Transpiration losses to riparian vegetation ranged from 0.78 m^3/sec. in April, to 1.54 m^3/sec. in July, under drought conditions. Requirements for irrigation were estimated to range from 5.56 m^3/sec. in May to 7.97 m^3/sec. in July, under drought conditions. It was concluded that flow requirements to satisfy monthly water losses to transpiration must be added to the base fishery flows to provide adequate protection to the resources in the lower reaches of the river.

Integration of the in-stream requirements for various use components shows that a base flow of at least 23.6 m^3/sec. must be reserved during the month of June to initiate scour of sediment from pools, provide spawning habitat for shovelnose sturgeon, and to accommodate water losses from the system. In comparison, a base flow of 3.85 m^3/sec. would be required during early February to provide fish rearing habitat and insect producitivity, and to prevent excessive loss of food production areas to surface ice formation. During mid to late February, a flow of 12 m^3/sec. would be needed to facilitate ice break-up and prevent ice jams from forming. Following break-up, the base flow would again be 3.85 m^3/sec. until the start of spawning season.

TABLE OF CONTENTS

Page

CHAPTER 1: INTRODUCTION 1-1

The Study Area 1-4
Geomorphology 1-4
Surface Water Resources 1-6
Fisheries Resources 1-8
References 1-11

CHAPTER 2: SUMMARY 2-1

CHAPTER 3: CONCLUSIONS 3-1

CHAPTER 4: RECOMMENDATIONS 4-1

Research Needs 4-5

CHAPTER 5: A COMPREHENSIVE METHODOLOGY FOR IN-STREAM FLOW DETERMINATIONS 5-1

Introduction 5-1
Water Quality Component 5-5
  Dissolved Oxygen 5-6
  Temperature 5-7
  Total Dissolved Solids or Discrete Salts 5-8
Fisheries Component 5-9
Ice Formation Component 5-12
Transpiration Loss Component 5-16
Sediment Transport Component 5-17
References 5-19

CHAPTER 6: IMPLEMENTATION OF THE FISHERY COMPONENT METHODOLOGY 6-1

Introduction 6-1
The Critical Area-Indicator Species Method 6-2
Determination of Flow Criteria 6-4
  Rearing Criteria with the Stonecat as Indicator 6-4
  Streamflow Criteria Based on Benthic Macroinvertebrate Studies 6-6
  Flow Criteria for Spawning 6-15
    Sauger Spawning 6-15
    Shovelnose Sturgeon Spawning 6-16
Measurement and Mapping of Hydrologic Parameters 6-19
  Multiple Transect Analysis (MTA) 6-19
  Flow Prediction Models Used with MTA 6-19
    Water Surface Profile Program (WSPP) 6-20
    CONTOUR Program 6-24

Page

Application of the Methodology 6-30
  Rearing Flow Recommendation Based on Stonecat Criteria 6-30
  Rearing Flow with *Rhithrogena hageni* as the Indicator 6-35
  Spawning Flow with the Shovelnose Sturgeon as the Indicator 6-35
References 6-41

CHAPTER 7: VALIDATION OF THE FISHERIES COMPONENT METHODOLOGY 7-1

Introduction 7-1
Reaction of Fish to Flow Reduction 7-2
  Results of Hydrologic Mapping 7-4
  Results of Fish Collections 7-4
Reaction of Aquatic Insects to Flow Reduction 7-15
Discussion of Methodology and Field Techniques 7-25
  Reproducibility 7-27
  Limitations 7-29
References 7-36

CHAPTER 8: ICE FORMATION 8-1

Mechanics 8-1
Biological Effects of Ice Formation 8-10
Water Requirements to Minimize Ice Problems 8-11
References 8-14

CHAPTER 9: CONSUMPTIVE USE BY RIPARIAN VEGETATION 9-1

Introduction 9-1
Groundwater Supply Mechanisms 9-2
Riparian Evapotranspiration on the Tongue River 9-3
  Methodology 9-3
  Computation of Evapotranspiration Rates and Correction for Precipitation 9-11
Irrigation: A Special Case of Evapotranspiration 9-14
Results and Discussion 9-20
References 9-25

Chapter 10: SEDIMENT TRANSPORT 10-1

Introduction 10-1
Sediment Sources 10-4
  Climatic Factors 10-5
  Geologic Factors 10-6
Methods and Materials 10-8
Results and Discussion 10-9
  Time and Scour Efficiency 10-15
  Methodological Assessment of Sediment Transport Studies 10-17
References 10-22

Page

CHAPTER 11: BIBLIOGRAPHY 11-1

CHAPTER 12: GLOSSARY 12-1

APPENDIX A: HYDROLOGIC CONTOUR MAPS; REARING AREAS A-1 - A-24

APPENDIX B: COMPOSITE MAPS; REARING AREAS B-1 - B-12

APPENDIX C: COMPOSITE MAPS; INSECT PRODUCTIVITY AREAS C-1 - C-12

APPENDIX D: MACROINVERTEBRATE ECOLOGY D-1 - D-66

APPENDIX E: HYDROLOGIC CONTOUR MAPS; SPAWNING CRITICAL AREA E-1 - E-17

APPENDIX F: COMPOSITE MAPS; SPAWNING CRITICAL AREAS F-1 - F-8

APPENDIX G: HYDROLOGIC CONTOUR MAPS; EXPERIMENTAL CHANNEL SECTION G-1 - G-18

APPENDIX H: COMPOSITE MAPS; EXPERIMENTAL CHANNEL SECTION H-1 - H-9

APPENDIX I: ICE FORMATION CROSS SECTIONAL DIAGRAMS I-1 - I-15

APPENDIX J: VEGETATION MAPS OF TONGUE RIVER FLOODPLAIN J-1 - J-40

APPENDIX K: SEDIMENT-DISCHARGE RATING CURVES K-1 - K-13

Paginated by source

LIST OF FIGURES

Figure		Page
1-1	Map of the Montana portion of the Tongue River Drainage showing primary study areas	1-5
1-2	Flow duration curve for the Tongue River at stateline and at Miles City, 1961-1970 water years	1-7
5-1	Component diagram of a comprehensive in-stream flow recommendation procedure	5-2
5-2	Example of integrated methodology used to determine the minimum streamflow requirement for the Tongue River during the month of June	5-4
5-3	Example of the construction of a depth contour map	5-11
5-4	Example of a composite map showing areas meeting flow criteria for the stonecat	5-13
5-5	Example of preferred area vs. discharge, or "peak of the curve" plot used to determine optimum and minimum streamflow requirements	5-14
6-1	Index map for macroinvertebrate studies, Tongue River, Montana	6-7
6-2	"Peak of the Curve" graph for determining optimum rearing flow, based on flow criteria for the stonecat, Viall Mapping Section	6-36
6-3	"Peak of the Curve" graph for determining optimum rearing flow, based on flow criteria for the stonecat, Orcutt Mapping Section	6-37
6-4	"Peak of the Curve" graph for determining optimum rearing flow, based on flow criteria for _Rhithrogena hageni_, Viall Mapping Section	6-38
6-5	"Peak of the Curve" graph for determining optimum spawning flow, based on flow criteria for the shovelnose sturgeon, Ft. Keogh Section	6-40
7-1	"Peak of the Curve" graph for Riffle #1, Experimental Channel Section, Viall Ranch	7-5
7-2	"Peak of the Curve" graph for Riffle #2, Experimental Channel Section, Viall Ranch	7-6
7-3	"Peak of the Curve" graph for Riffle #1, Experimental Channel Section. Gravel areas omitted.	7-7

Figure		Page
7-4	Fish Distribution in Experimental Channel, Q = 2.01 cms.	7-11
7-5	Fish Distribution in Experimental Channel, Q = 1.33 cms.	7-12
7-6	Fish Distribution in Experimental Channel, Q = 1.07 cms.	7-13
7-7	Drift during the period of flow reduction, all invertebrates	7-18
7-8	Drift during the period of flow reduction, Ephemeroptera	7-19
7-9	Drift during the period of flow reduction, Plecoptera	7-20
7-10	Drift during the period of flow reduction, Hemiptera	7-21
7-11	Drift during the period of flow reduction, Coleoptera	7-22
7-12	Cumulative distribution curve of June streamflow in the Tongue River, 1961-1974	7-34
8-1	Cross sectional diagram of surface ice sheet at SH Ranch section	8-4
8-2	Cross sectional diagram of surface ice sheet at Viall Ranch section	8-5
8-3	Cross sectional diagram of surface ice sheet at Birney Ranch section	8-6
8-4	Relationship between current velocity and ice thickness in the Tongue River during the winter of 1974-1975	8-7
9-1	Hydraulic gradient of floodplain groundwater in straight and meandering channels	9-3
10-1	Criteria for scour, median size less than 5 mm.	10-18

LIST OF TABLES

Tables		Page
1-1	Fish species inhabiting the Tongue River as determined by electrofishing during 1974.	1-9
5-1	Expected ice thickness derived from current velocities at measurement locations.	5-15
6-1	Occurrance of stonecats with respect to depth and current velocity.	6-5
6-2	Relationship between diversity of aquatic invertebrates and current velocity and depth.	6-11
6-3	Relationship between diversity of aquatic invertebrates, and turbulence and bottom configuration.	6-12
6-4	Frequency of occurrance of ripe shovelnose sturgeon, according to depth and velocity groupings.	6-17
6-5	Flow criteria for spawning shovelnose sturgeon as determined by the combination of depth and velocity classes.	6-18
6-6	Predicted and measured water surface elevations (meters) at SH section, at 2.38 cms.	6-22
6-7	Comparison of predicted and measured velocities in cm./sec. at Transect C, Viall Section.	6-23
6-8	Comparison of predicted and measured velocities in cm./sec. using the CONTOUR Program, Transect C, Viall Section.	6-26
6-9	Comparison of predicted and measured velocities in cm./sec. using the CONTOUR Program, Transect C, Viall Section.	6-27
6-10	Comparison of predicted and measured velocities in cm./sec. using the CONTOUR Program, Transect C, Viall Section.	6-28
6-11	Comparison of predicted and measured velocities in cm./sec. using the CONTOUR Program, Transect C, Viall Section.	6-29
6-12	Comparison of predicted and measured depths, using the CONTOUR Program.	6-31
6-13	Comparison of predicted and measured depths, using the CONTOUR Program.	6-32
6-14	Comparison of predicted and measured depths, using the CONTOUR Program.	6-33

Table		Page
6-15	Comparison of predicted and measured depths, using the CONTOUR Program.	6-34
7-1	Number of Individuals of Each Species Collected at Four Experimental Flows.	7-8
7-2	Species Diversity at Four Experimental Discharges.	7-9
7-3	Change in average velocity at nine habitat areas in experimental channel. Velocities in cm./sec.	7-14
7-4	Change in average depth at nine habitat areas in experimental channel. Depth in cms.	7-14
8-1	Approximate percentage of channel area frozen from surface to streambed at various discharges at Viall Ranch Section during a winter of normal severity.	8-13
9-1	Total canopy cover and canopy cover per km. for the Tongue River from T & Y Diversion to above Ashland, Montana.	9-7,8
9-2	Climatological data for Miles City, Montana.	9-12
9-3	Inputs to Penman equation, derived using climatic data from Table 9-2.	9-13
9-4	Effective precipitation, evapotranspiration, and net evapotranspiration deficit; based on local climatological data and the Penman equation.	9-15
9-5	Mean daily evapotranspiration, corrected mean daily evapotranspiration, and mean daily maximum evapotranspiration rates.	9-16
9-6	Mean daily, rainfall-corrected mean daily, and mean daily maximum instantaneous flow requirements for riparian vegetation on the Tongue River.	9-17
9-7	Mean daily instantaneous flow requirements and rainfall corrected mean daily instantaneous flow requirements for irrigated crops, riparian, and total vegetation on the Tongue River.	9-19
9-8	Water budget for lower Tongue River basin to test accuracy of calculated values of evapotranspiration.	9-21
10-1	Analysis of suspended sediment load for several locations on the Tongue River and tributaries.	10-10
10-2	Analysis of bedload for several locations on the Tongue River and tributaries.	10-11

LIST OF PLATES

Plate		Page
7-1	Diversion structure, island, and experimental channel at Viall Ranch Section.	7-3
8-1	Pumping station at the SH Ranch which was nearly destroyed by ice jamming in February, 1975.	8-12
9-1	Aerial photograph showing canopy cover of the riparian vegetation of the Tongue River floodplain, in the vicinity of Ash Creek.	9-5
9-2	Vegetation map showing canopy cover density as estimated from the aerial photo of the Tongue River floodplain near Ash Creek.	9-6

PREFACE

This report is submitted in fulfillment of contract #68-01-2653, issued by Region VIII of the U.S. Environmental Protection Agency, to Dr. Arnold Silverman, Department of Geology of the University of Montana, Missoula, Montana.

One of the most enjoyable aspects of a project with the variety and diversity of this one, is the constant opportunity to learn and share ideas with experts from a wide range of disciplines. We have indeed been fortunate to have received so much help from agency personnel at both the state and federal levels.

We are indebted to Mr. Harold Fabricius, U.S. Geological Survey Sedimentation Laboratory, Worland, Wyoming, whose advice and guidance was invaluable in setting up a smooth running sediment laboratory in Miles City. We are also indebted to Mr. Ralph Hurlburt, and the staff and administration of Miles Community College, who donated laboratory space and allowed free use of the college's equipment when needed.

Thanks are extended to Mr. Allen Elser, fisheries manager of Region 7, Montana Department of Fish and Game, who allowed unlimited use of his personnel and equipment during this study. A special note of thanks is offered Mr. Robert McFarland, Tongue River Project Leader, for the Montana Fish and Game Department, who always had a place in his boat for our studies and often took time out from his own work when help was needed.

This project was administered through the offices of EPA, Region VIII, Mr. Loys Parrish, Project Officer. We are grateful to Mr. Parrish and Mr. Denis Nelson, also of EPA Region VIII, for their persistence and patience to ensure funding, and for their suggestions during the

course of the study. The diligence and guidance of Mr. John McBride, Administrative Assistant to Dr. Silverman, is also gratefully acknowledged.

We wish to thank the ranchers and landowners along the Tongue River, who allowed access through their land to the study areas. Without their cooperation, the project could not have been successful. A very special thank you is extended to Mrs. Lillian Viall, and Mr. Bruce Orcutt, who not only allowed access, but freely offered encouragement, advice, and sometimes meals, during our visits to their ranches. Their interest in the project made the field work much more enjoyable.

CHAPTER 1: INTRODUCTION

Historically, protection of aquatic resources has focused on reduction or elimination of water pollution, avoidance of channelization or other modifications of the streambed, or effecting changes in land-use to ameliorate problems of non-point pollution. Potential energy and water resource developments in the Northern Great Plains have added a new dimension to the problems of aquatic habitat protection. For the first time, large river systems are now threatened with a substantial reduction of water during part or all of the year.

In addition, industrial development in the sparcely populated region is likely to be accompanied by a substantial population influx. The increase in population will place a greater load on the waste assimilation capacity of local rivers. Concurrently, fishing pressure and other recreational use of lakes and rivers will probably increase. The potential impact of increased demands on a depleted resource is a difficult managerial problem.

At least partial protection of the aquatic resource may be accomplished with the use of a "streamflow reservation." Essentially, this is a water right held by the state stipulating a specified discharge to be left within the confines of the natural channel. This discharge may be seasonally varied to fulfill a particular biological requirement, such as migration and spawning of fish, or a physical requirement, such as increasing flow to reduce ice jamming.

There are numerous methodologies available for the recommendation of in-stream flow needs. While many methodologies address the problems of water quality, sediment transport, riparian vegetation demands, ice formation, etc., the final flow recommendation invariably is based on the needs of the fishery. Thus, it is implicitly assumed that once the basic requirements of the fishery have been satisfied, other stream functions will also be adequately protected.

It is further assumed that most in-stream uses have an "extinction point", that is, a volume of water below which a given use cannot exist. This assumption may pressure the water resource planner to attempt to define the extinction point in order to maximize off-stream uses. This approach will most likely overlook complex, long-term physical or biological interactions, which will eventually result in preserving a mere vestige of former aquatic resources.

Consequently, the fundamental question in any water development scheme is, "How will this use conflict with existing stream uses?" Stated another way, "How much water must remain in the channel to maintain a viable ecosystem, provide for normal hydrologic functions, and satisfy existing uses by riparian and irrigated vegetation?"

Stalnaker and Arnette (1976) state that there is no single, comprehensive methodology for assessing all the different instream flow requirements. They suggest a standardized set of methodologies best suited to a chosen level of planning, resolution, and category of analysis. Unfortunately, many of these methodologies have only been assessed theoretically, with little or no case-history to determine the outcome of following, or not following, a minimum flow recommendation. In addition, most methodologies do not have provisions for testing the requirements of the many other in-stream uses besides fisheries.

In the Northern Great Plains, this problem is complicated by the fact that the rivers contain warm water fish communities. Experiences gained from studies of the dewatering of small mountain trout streams may not be entirely adequate for dealing with these large and complex streams. Even the basic data gathering techniques are subject to modification for use in the large river system.

This study has several distinct, but inter-related objectives. A primary objective is the development and field testing of a methodology designed to assess streamflow requirements of a warm-water fishery (Bovee, 1974). Details of the methodology are given in Chapter 5. Another primary objective is the assessment of several non-fishery in-stream flow needs (riparian vegetation, ice formation, and sediment transport) and evaluation of the adequacy with which the fishery flows meet these other needs. A secondary objective of the study is the evaluation and development of field techniques for assessing in-stream needs applicable for use in large rivers.

This report is divided into two sections. Section 1 deals with in-stream flow requirements based on the various needs of the fishery. Section 2 concerns itself with flow requirements based on non-fishery needs. Because of the large and varied amount of raw data required for a study of this type, it is practical to present only the synthesized data in the text. This approach may cause some confusion, as the derivation of answers to certain questions may not be intuitively obvious from the text. Therefore, a complete series of appendices are included at the end of the report. These will consist primarily of data maps, charts, and tables used in the solution of each subject problem.

To reiterate, this report will specifically address the methodological processes by which fishery and non-fishery flow requirements are determined. In addition, the report will attempt to show valid techniques for increased efficiency of data collection. Finally, the report will address the decision-making process, and discuss the type of input required for this process.

The Study Area

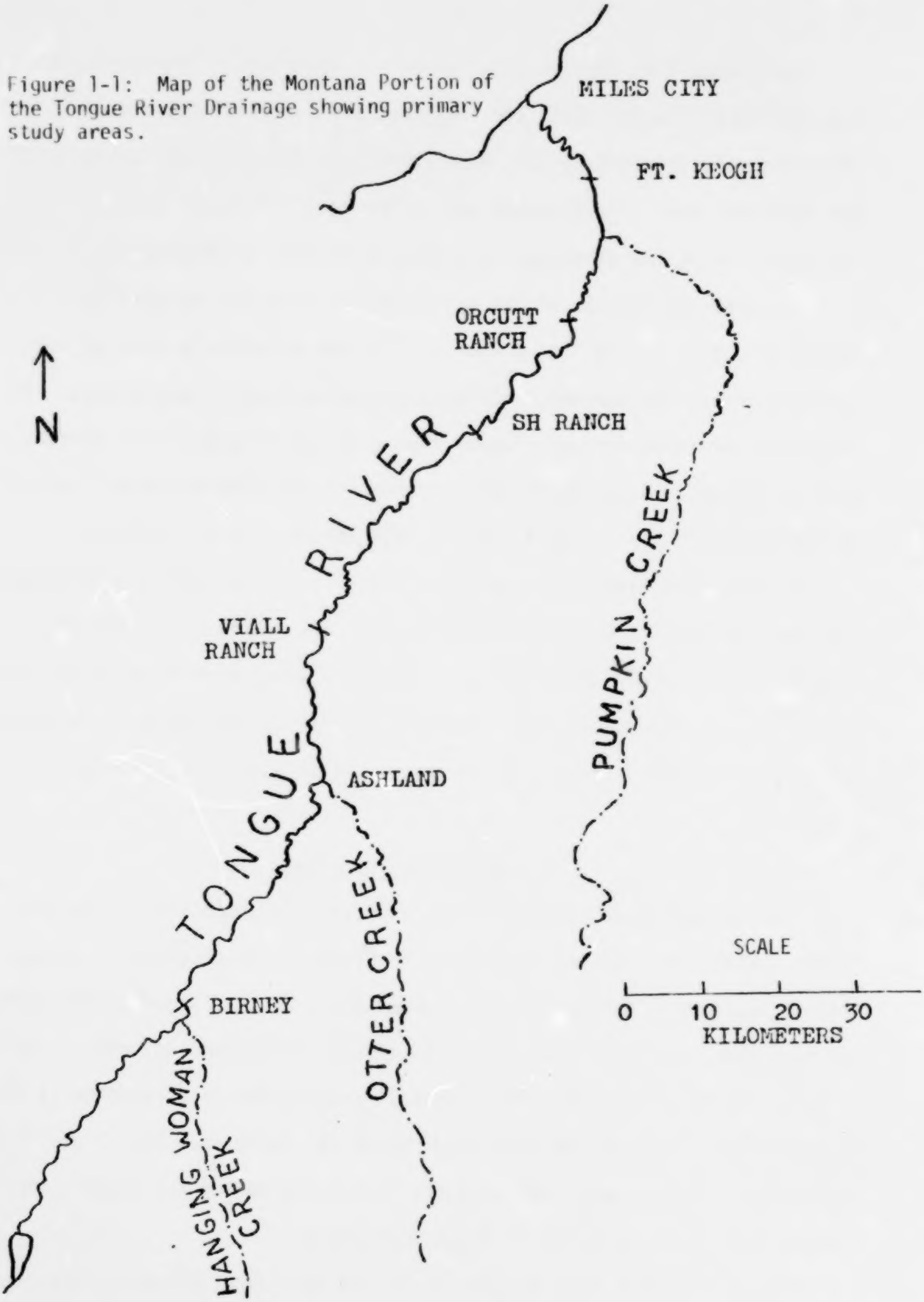
The Tongue River in southeastern Montana was chosen as the study area for this research project. Selection of this river was made on the basis of its size, location, and composition of the fish community. The Tongue is a medium sized river, with a bankfull discharge of approximately 45 m^3/sec. The average river width is about 50 meters.

Originating in the Bighorn Mountains of northern Wyoming, the Tongue River drains an area of 3825 km^2 before entering Montana near the town of Decker. Streamflow is regulated by the 60 million cubic meter Tongue River Reservoir, located near the Montana-Wyoming border. For the first 16 km below the dam, the river flows through a rugged canyon. From the mouth of the canyon, it meanders broadly across a wide valley as it flows northeast the remaining 290 km to the Yellowstone River. At Miles City, the total drainage area is 18,516 km^2 (U.S.G.S. Water Supply Paper #1916, 1969). Figure 1-1 is a map of the Montana portion of the Tongue River, showing its major tributaries and study sites.

Geomorphology

Despite a fairly high width-to-depth ratio, on the order of 50:1 in many places, the Tongue River is an incised stream for most of its length. Baker (1929) described the upper reaches of the basin as a recently uplifted area in the process of dissection. He indicated that the uplift began in early Tertiary time and has since been intermittent as shown by the many gravel covered benches and stream cut terraces along the Tongue River.

Figure 1-1: Map of the Montana Portion of the Tongue River Drainage showing primary study areas.



The Tongue River basin is an asymetric watershed. Tributaries entering the river from the south and southeast are typically twice as long as those entering from the north. Bass (1932) and Pierce (1936) concur that the basin has been tilted upward and to the east. This has resulted in the extension of the north and west flowing streams by headcutting.

The combined effects of the uplift and tilting has resulted in a unique situation in the Tongue River. Although draining an area of high sediment yield, the streambed of the river is armored in many places. The substrate particles are much larger than would be expected in a "typical prairie stream." Armoring is most apparent in the upstream areas, and it is possible that the Tongue River Dam contributes to this condition.

As the river approaches its lower reaches, the sediment yield increases and the substrate size noticeably decreases. Below the confluence of Pumpkin Creek, the Tongue River gives way to a sandy bottom and gravel bars typical of an alluvial stream. Complete details of the geology, structure, and sediment characteristics of the Tongue River basin are discussed in Chapter 11.

Surface Water Resources

The average annual precipitation at Miles City, Montana, is 309 mm. (NOAA, 1972). For the entire basin, the average precipitation is around 340 mm. per year. Of this total, approximately 47% falls during the months of May, June, and July. Due to the high rate of evaporation, only a small fraction (2 to 15%) of the total rainfall contributes to streamflow in the Tongue River. Most of the water flowing in the Tongue has its origin in the headwaters. During parts of the year, especially during the summer, the Tongue River loses water as it flows downstream.

Figure 1-2 is a flow duration curve for the Tongue River at stateline and at Miles City, MT. It is interesting to note that the two curves are

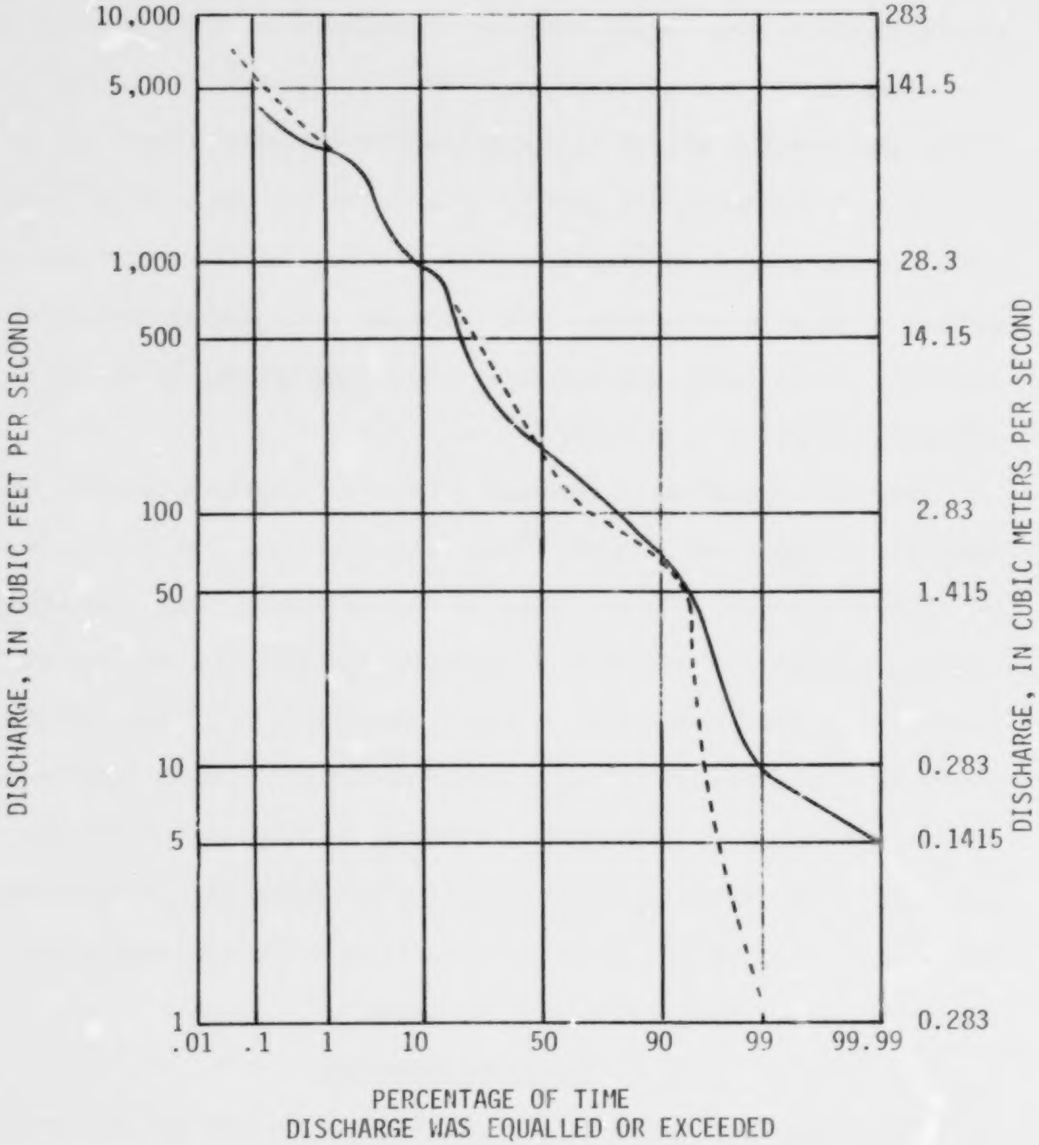


Figure 1-2: Flow Duration Curve for the Tongue River at stateline (solid line) and at Miles City (dashed line), 1961-1970 water years.

nearly identical even though the size of the basin at Miles City is nearly five times larger than at stateline. This is a further indication that little additional discharge is accumulated in the lower river.

By most standards, the quality of water in the Tongue River is good. There are few sources of organic pollution along the river, and the oxygen content is usually quite high. The two major water quality problems, turbidity and salinity, are naturally occurring, but may be seriously influenced by man's activities.

When the streamflow is composed primarily of surface run-off, the turbidity of the river is high. This is particularly true in the lower river where there is a large source of fine sediment. When streamflow is composed primarily of influent groundwater, turbidity is low, but the concentration of dissolved solids is high. Hopkins (1973) found that the concentrations of dissolved solids varied from 674 mg/L when streamflow was low, to 190 mg/L when it was high. Principal cations are sodium and potassium, with smaller amounts of calcium and magnesium. Bicarbonate is the primary anion, with substantial amounts of sulfate in some places, depending on the aquifer supplying the water.

Fisheries Resources

The Tongue River supports a productive and diversified warm water fishery. Table 1-1 lists the species inhabiting the Tongue River as determined by electrofishing during 1974. Most of the species listed in Table 1-1 are resident fish. However, the shovelnose sturgeon and the blue sucker inhabit the river in greatest numbers during the spring, indicating that the river is an important nursery area for these species. Thus, any alteration to the Tongue River may also have profound effects on the fishery of the Yellowstone River.

The Tongue River is a popular fishing stream for many local inhabitants.

Table 1-1: Fish species inhabiting the Tongue River as determined by electrofishing during 1974.

Common Name	Scientific Name
Carp	*Cyprinus carpio* (Linnaeus)
Flathead Chub	*Hybopsis gracilis* (Richardson)
Sturgeon Chub	*Hybopsis gelida* (Girard)
Longnose Dace	*Rhinichthys cataractae* (Valenciennes)
Silvery Minnow	*Hybognathus nuchalis* (Agassiz)
Shorthead Redhorse	*Moxostoma macrolepidotum* (Le Sueur)
White Sucker	*Catostomus commersoni* (Lacepede)
Longnose Sucker	*Catostomus catastomus* (Forster)
Mountain Sucker	*Catostomus platyrhynchus* (Cope)
River Carpsucker	*Carpiodes carpio* (Rafinesque)
Blue Sucker	*Cycleptus elongatus* (Le Sueur)
Shovelnose Sturgeon	*Scaphirhynchus platorynchus* (Rafinesque)
Goldeye	*Hiodon alosoides* (Rafinesque)
Mountain Whitefish	*Prosopium williamsoni* (Girard)
Rainbow Trout	*Salmo gairdneri* (Richardson)
Brown Trout	*Salmo trutta* (Linnaeus)
Northern Pike	*Esox lucius* (Linnaeus)
Black Bullhead	*Ictalurus melas* (Rafinesque)
Channel Catfish	*Ictalurus punctatus* (Rafinesque)
Stonecat	*Noturus flavus* (Rafinesque)
Burbot (Ling)	*Lota lota* (Linnaeus)
Rock Bass	*Ambloplites rupestris* (Rafinesque)
Green Sunfish	*Lepomis cyanellus* (Rafinesque)
Pumpkinseed	*Lepomis gibbosus* (Linnaeus)
Smallmouth Bass	*Micropterus dolomieue* (Lacepede)
White Crappie	*Pomoxis annularis* (Rafinesque)
Black Crappie	*Pomoxis nigromaculatus* (le Sueur)
Yellow Perch	*Perca flavescens* (Mitchell)
Sauger	*Stizostedion canadense* (Smith)
Walleye	*Stizostedion vitreum* (Mitchell)

Fishing pressure is concentrated in areas of easy access and near population centers. A lack of public access areas is a problem along the river. However, most landowners will allow access to fishermen who request it. Such private access areas tend to be under-utilized, consequently fishing success is usually high, and is sometimes spectacular. Catches of sauger in the 1 - 2 kg range are not uncommon, channel catfish weighing 4 to 6 kg are occassionally caught, and large, active smallmouth bass are plentiful in many sections.

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CHAPTER 2: SUMMARY

A comprehensive methodology for the assessment of in-stream flow needs was implemented in the Tongue River in southeastern Montana. The methodology consists of the determination of the individual flow requirements for a number of in-stream uses. Some of these "component" uses are considered complementary; the flow requirement for one use will satisfy the requirements for several other uses. However, uses such as the consumptive loss of water by riparian vegetation and irrigation are considered additive. Because these uses actually remove water from the system, their requirements must be considered separately to determine the total water requirements needed to ensure the protection of the complementary uses.

The complementary uses examined included: 1) Fisheries requirements for spawning, rearing and aquatic invertebrate production; 2) Sediment transport; and 3) Ice mitigation requirements, including habitat losses to ice formation and flow requirements to prevent ice jams from forming.

A flow requirement for a given period of time is determined by examining the flow requirements for each of the complementary uses. The greatest minimum flow requirement for all complementary uses is selected as the critical minimum requirement. The total in-stream flow requirement is then determined by adding the total consumptive losses to this critical minimum flow for the time period in question (See Figure 5-1, 5-2).

The methodology uses in the assessment of the fishery flow requirements utilizes two separate but inter-connected concepts. The first of these is the critical area concept, by which areas of the stream most likely to be affected by reduced streamflow may be identified. The second is the use of an indicator species, an inhabitant or user of the critical area, that is highly selective of the hydrologic and substrate parameters found in critical areas. The methodology is based on the hypothesis that adequate protection of the critical area habitat will result in equally satisfactory protection of other habitat areas and the inhabitants therein.

Implementation of the methodology consists of: 1) determining flow criteria (preferred conditions of depth, velocity, and substrate) for each of several indicator species, and 2) assessing the amount (area) of preferred habitat available in the critical area over a range of discharges.

Several indicator species were examined and flow criteria determined for each. The sauger (Stizostedion canadense) and shovelnose sturgeon (Scaphirhynchus platorynchus) were selected as spawning flow indicators, while the stonecat (Noturus flavus) was selected as a rearing flow species. Productivity of aquatic insects, as a function of hydrologic conditions, was also evaluated. The mayfly nymph, Rhithrogena hageni, was selected as the species whose optimum flow conditions most closely corresponded to those for highest overall diversity and biomass.

Study of the stonecat showed it most commonly associated with substrate particles 128 to 256 mm. in diameter, with considerable utilization of substrate sizes ranging from small cobbles to boulders. Flow criteria for the stonecat was established at depths between 30 and 60 cm. and velocities between 45 and 90 cm./sec., over a cobble substrate.

It was determined that depths of 20 to 40 cm., with velocities of 75 to 120 cm./sec., over a bottom composed of combined smooth and angular cobble, provided the greatest diversity and biomass of aquatic insects. This corresponds well with the optimum conditions for the productivity indicator species, Rhithrogena.

During the spawning run, large concentrations of sauger were found in water depths of 74 to 105 cm., with velocities from 64 to 90 cm./sec., typically over a fine to coarse, dune-form, sandbed. Unfortunately, these flow parameters should not be used as flow criteria, as ripe females were not collected during the two month sampling program.

Ripe shovelnose sturgeon of both sexes were collected in moderate numbers during their spawning run. Criteria included depths of 60 to 100 cm. and velocities from 70 to 110 cm./sec. over a sand, or sand and gravel, substrate.

Optimum flow conditions for rearing, insect productivity, and spawning were evaluated using the multiple transect method of analysis developed by Collings, et. al. (1972). Hydrologic maps showing areas of equal depth, velocity, and substrate type (where applicable) were prepared from data collected at selected critical areas. For rearing and productivity, the best areas for study are the riffles, which form complete control of the flow (at approximate right angles to the flow). For spawning, the best critical areas are usually gravel bars and shoals which, when covered by water, show a moderate current velocity.

One finds that the optimum rearing flow, using the stonecat as the indicator species, is around 11.5 to 12.0 cms. (400 to 425 cfs.). This corresponds to the optimum productivity flow as determined by using *Rhithrogena* as the indicator species. The optimum spawning flow was estimated to be 50 cms. from the discharge-preferred area curve.

A section on the field tested results of two flow prediction models are reported in Chapter 6. The Water Surface Profile Program was developed by the U.S. Bureau of Reclamation, and is an energy balance model using surveyed channel and water surface elevation data in conjunction with the Manning equation. The CONTOUR Program, developed during this study, utilizes hydraulic geometry measurements made at two or more discharges. Data from each point on each transect is subjected to a power function equation by logarithmic regression. For each point on the transect, it is possible to predict the depth and velocity at various flows, as well as the width of the transect. Each model gave reasonable results, and either can be of great utility in in-stream flow work.

The validity of the fisheries component methodology developed in this study, its limitations, and possible ways to overcome the limitations by changes in procedure and/or equipment are examined in Chapter 7. To be judged reliable, a methodology must be tested against two standards or criteria. First, the method should give accurate and reproducible results. Secondly, these results must agree with measurements or observed phenomena in the field. To be valid the methodology must also give results that meet the criteria of water availability.

It was determined that basing the minimum streamflow requirement on a percentage of the optimum flow is not a valid procedure. For the Tongue River the natural streamflow was less than the methodology's recommended minimum about 60% of the time. Therefore, it was necessary to introduce a new concept, the base flow, for the determination of minimum flows. The base flow is defined as that discharge which first provides some area meeting the flow criteria for a given indicator species over the selected critical area. Utilization of the base flow concept allows a much more objective means of determining the minimum streamflow requirement.

Two field tests were conducted to determine the validity of the base flow concept. During the fall of 1975, a small diversion structure was constructed in an island side channel of the Tongue River. Experimental streamflows were adjusted and maintained in the channel by diverting water into or out of the channel. Two hydrologic mapping sections were established in the experimental channel, and contour maps drawn for several discharges. Once an experimental flow had been set, it was maintained for a two week stabilization period. At the end of this time a block net was erected at the lower end of the channel and the channel sampled with electrofishing gear. We found that at the optimum flow, as determined by our methodology, the channel had its highest diversity, the greatest number of sport and game fish, and the largest number of the indicator species occupying the critical area. Conversely, at the discharge corresponding to our determined base flow, the diversity was the lowest, neither game nor sport fish were present, and the indicator species was no longer found over the critical area.

The second field test took advantage of the closure for repairs of the Tongue River dam. Drift samples of aquatic insects were collected for a 48 hour control period prior to closure. During this time, a normal diurnal pattern was observed, with a peak of about 150 animals captured per 4-hour period. The base flow, as determined from the methodology using *Rhithrogena* as the indicator, was around 3.70 cms. When the streamflow fell below 3.69 cms., massive drift of all species was observed. Almost a 10-fold increase in the number of drifting animals occurred the first night. Although a diurnal pattern was maintained, the number of individuals in the drift was elevated during both day and night collections. Interestingly, *Rhithrogena* made up 10% to 20% of the Ephemeroptera in the drift once the stream flow levels declined below base flow. Prior to the decline in streamflow this species was not found in the drift in appreciable numbers.

We concluded, therefore, that the base flow concept was indeed valid. A base flow of 3.70 cms. in the Tongue River was equalled or exceeded at least

75% of the time for the water years 1961-1970. Thus, base flow also meets the criteria of water availability.

Also, base flow for sturgeon spawning was determined to be 13.0 cms., based on an inflection point occuring on the discharge-preferred area curve, and on examination of the spawning composite maps. It is not realistic to compare this flow requirement with the annual flow duration curve. Rather, the spawning base flow was compared with the probability curve for discharges during the month of June for the water years 1961 through 1974. We found that the probability of a streamflow greater than 18 cms. during June was 83%. On this basis we conclude that the spawning base flow is also reasonable in terms of water availability.

Chapter 8 deals with the formation of ice in rivers and the effects of reduced streamflow during the winter and early spring. Unlike many mountain streams, the most serious ice problem in prairie rivers is the formation of surface, rather than frazile or anchor ice.

During the winter of 1974-1975, the ice thickness was measured at several cross sections. Current meter measurements were made with each thickness measurement. When the thickness of the ice was plotted against current velocity, an inverse relationship was apparent.

The mechanics of ice formation were studied in some detail, at the Orcutt ranch section during the winter of 1975-1976. In the initial stages of freezing, the thickness of the ice was nearly uniform. As freezing continued, it was obvious that areas of low velocity thickened at a higher rate than areas of high velocity. For a given temperature regime, each location showed a cessation of thickening after an initial period of growth. An insurgence of colder temperature caused a resumption in ice growth at each location until a new equilibrium thickness was reached. It was hypothesized that this phenomenon is caused by the addition of frictional heat from the running water, which prevents or retards the thickening process. Faster running water has more kinetic energy, and therefore adds heat at a higher rate. This hypothesis, however, has not been confirmed to date. Because of the effect of current velocity on ice thickness, we conclude that reduced discharge would not only reduce the depth of the water, but also result in a thicker ice cover. This could result in larger areas of the stream being solidly frozen from top to bottom. The most obvious effect of such encroachment would be the loss of habitable area for insects and fish alike. Because of the large drag effect of the ice where the water envelope (the space between the stream bed and the bottom ice surface) is small, many areas not frozen to the bed may have insufficient velocities to support certain species. In addition, since the discharge is not affected by freeze-up, the same discharge must be conveyed through an ever-decreasing channel cross section. As a result, significant increases in velocity were observed in the thalweg areas, where the excess water was channeled by the blocking ice pack.

We further determined that insufficient discharge during the break-up period would result in an increased probability of ice jam formation. These ice jams most certainly have an impact on the inhabitants of the river, but the extent of the impact is yet unknown. In addition, the phenomenon is a clear threat to man-made structures as well, and should be avoided if possible.

Based primarily on the findings of the 1974-1975 ice monitoring program, and on the hydrologic contour maps for the Viall section, it was possible to estimate the water requirements to minimize ice formation and break-up difficulties. At a flow of 2.83 cms., the base flow from stonecat criteria, up to 80% of the riffle area would be frozen solidly to the bottom, with a potential loss of circulation in some downstream areas. At a flow of 4.02 cms., near the base level for *Rhithrogena*, 50% to 60% of the control would be frozen tight during a winter of normal severity. And finally, at 5.58 cms., a flow well above base flow, 20% to 30% of the control would still be lost to ice.

Flow requirements to reduce ice jamming were also determined. At the Viall section, it is likely that serious ice jams will occur at flows less than 5.6 cms. At least 10 cms. would be required to ameliorate ice jamming, although it would still occur. A flow of from 19 to 20 cms. would probably be sufficient to prevent ice jams at this section.

Two thermodynamic models for predicting equilibrium ice thickness are also presented in Chapter 8. The equilibrium thickness equation developed by Paily, et. al. (1974) shows great promise for future use with in-stream flow studies. However, the relationship between velocity and frictional heat production must be investigated before this equation becomes generally applicable.

Consumptive use of water and in-stream flow requirements for riparian vegetation are the subjects of Chapter 9. The mechanics of water supply were also studied to determine whether the vegetation was living on stored water, or a continuously available supply. Core samples showed that the floodplain is composed primarily of unconsolidated sand, gravel, and cobble, and that the particle size of the alluvium was greatest at root depth for most trees. It was determined that the riparian vegetation was not only continuously supplied with river water, but also that the transmissivity of the floodplain was so high that the rate of supply may exceed the rate of loss to evapotranspiration. The size of the meander bend was also thought to influence the extent of the vegetation cover. On smaller bends, the peizometric surface is probably planar, or nearly so. On the larger bends, the water demand by vegetation, or losses to storage, may create a cone of depression near the center of the meander peninsula. As a result the interiors of many large meander loops are not vegetated by phreatophytes.

Total consumptive use of water was determined in two phases. First, the total area of canopy cover was found by constructing vegetation maps from aerial photos. Each vegetated area on each map was given a weighting factor based on the percent of the total area actually occupied by canopy. The vegetated areas were then measured by polar planimeter and the area multiplied by the appropriate weighting factor to give the average canopy cover. Total canopy cover was determined by multiplying the average canopy cover per mile of river, by the total length of river under study. The total canopy area for the lower Tongue River was calculated to be 1970 hectares.

The rate of potential evapotranspiration was found using a variation of the Penman energy balance equation, and local climatological data. The average monthly effective precipitation (storms greater than 2.5 mm. of rain per day) was subtracted from the monthly potential evapotranspiration to obtain a mean monthly "evapotranspiration deficit."

The mean daily and mean daily maximum evapotranspiration rates were calculated using mean daily and mid-day climatological inputs. The maximum daily rates were computed because of the high transmissivity of the floodplains. As the instantaneous flow requirement will probably be satisfied quickly, the daily maximum rate of use is important to in-stream supplies.

The highest rates of consumption occur in June, July, and August. The rainfall corrected instantaneous flow requirements for those months are 0.90, 1.29, and 1.20 m^3/sec., respectively. During a drought period, the mean daily rates of water withdrawal were calculated to be 1.31, 1.54 and 1.36 cms.

for those months. The mean daily maximum flow requirements are 1.69, 1.94 and 1.76 cms., respectively.

Irrigation was considered a special case of evapotranspiration, and the instantaneous flow requirements for irrigation were also calculated in the same fashion, based on an irrigated area of 10,200 hectares. The rainfall-corrected flow requirement for irrigated crops is estimated to be 4.68, 6.67 and 6.25 cms. for June, July, and August, respectively. The total rainfall-corrected flow requirement for all riparian vegetation was calculated to be 5.58, 7.96, and 7.45 cms. for those months.

These flow requirement calculations were tested using a water balance equation. Inflow to the basin was calculated from stream gaging records at the Tongue River Reservoir and monthly precipitation records for the basin. Outflow included the streamflow at Miles City, the potential volume of evapotranspiration, evaporation, and storage. Because evaporation and storage were virtually impossible to estimate, they were eliminated from the equation by selecting months when little or no rain fell, and was thus, not available for evaporation or storage.

The results obtained from the water balance equation were consistent with actual streamflow measurements. The error between the predicted outflow at Miles City, and that measured, was less than 10% for most dry months. The flow requirements obtained are considered conservative, because the calculated outflow was consistently greater than the measured outflow, particularly for months with some measurable precipitation.

Chapter 10 deals with the subject of sediment transport in the Tongue River. Sediment deposition causes problems not only for the fishery, but also with man-made structures such as bridges, diverison dams, and irrigation systems.

The study of sediment transport was divided into the hydrologic functions (watershed sources) and the hydraulic functions (sediment removal). Of the hydrologic functions, the effects of climate, lithology, and geologic structure are important factors in the supply of sediment to the river.

The climate is important because sufficient rainfall occurs to promote erosion and runoff, but not enough to provide a good stabilizing vegetational cover. Also, during spring snowmelt the basin behaves as if underlain by permafrost. Thawed layers of soil are water saturated, while lower layers remain frozen. This results in rapid runoff and very high sediment yield.

The lithology of the basin is especially interesting. The upper basin surface consists primarily of the Tongue River member of the Fort Union formation. This unit is highly fractured and resistant to weathering. Most of the precipitation which reaches the mainstem Tongue River from this lithologic unit, does so as groundwater. The surface of the lower Tongue River basin is composed of the Lebo shale member, which is easily weathered and eroded. However, sediment samples collected from tributaries in the Lebo shale show that most of the sediment derived from this unit is so fine that it passes through the system as suspended load. Much of the coarse sediment in transport originates in the streambed and banks of the Tongue River itself. Of the major extraneous sources of large sediment particles, the most important is material which slumps into the river from the numerous terraces along the river. This source is important because it is not necessarily streamflow related, as are most other sources. Therefore, large size sediment frequently enters the stream at times other than high flow.

From data collected during the 1975 runoff season, it was determined that sediment entering the river via tributaries would be a minor problem because of the small size of the particles. It was further determined that the bed becomes less stable and more prone to aggradation in the lower part of the basin. The greatest potential for aggradation probably occurs in the lower 20 km. of the Tongue River below the confluence of Pumpkin Creek.

During the 1976 runoff season, a sediment sampling station was established in this lower reach. Samples were collected at two or three day intervals during the rising limb of the spring runoff curve. The purpose of the monitoring program was to attempt to determine the discharge required to initiate pool scour in this section.

Total suspended sediment, suspended silt-clay, and suspended sand loads were plotted against discharge, as were the various size fractions of bedload. A sharp break wasn't found in any of the curves to clearly suggest the initiation of scour. However, trend fitted curves plotted to data clusters indicated that there was an acceleration in movement of fine to medium sand as dominant bedload between 18.0 and 25.0 cms. This finding was supported by the increased amount of fine sand in suspension at the same range of flows. We suggest that 18.0 cms. is the lowest discharge at which pool scour would occur. Apparently 20.0 to 25.0 cms. would be required for a high enough rate of removal to scour the pools effectively. Even at 25.0 cms. true bed mobility had not yet occurred, and it is likely that the sediment in motion was recently deposited and loosely packed, and, therefore, readily transportable.

Scour efficiency was also discussed in Chapter 10. If the lowest scouring flow is selected for sediment removal, the flow must be maintained for a long period of time. The use of higher flows for a shorter period would probably be a more efficient use of water. However, maximizing the scour efficiency by releasing a large volume of water for a short period of time to achieve pool scour should be avoided. It could result in the deposition of coarse materials where fines once occurred, thereby armoring the bottom and making scour more difficult in succeeding years. In addition, such an increase and following decrease in flow would undoubtedly damage the instream resources which the scour was to have benefited.

Several sediment transport models are discussed in Chapter 10, although they were not used or field tested in this study. Tractive force (shear stress) models are simple and easily applied to the problem of scour. However, the single greatest failing of this method is the inadequacy in determining the critical tractive force (the shear stress needed to move a certain size of particle) in a matrix of various particle sizes. The most reliable method of determining critical tractive force is by empirical testing. If this method is used, the tractive force model becomes academic, as the discharge at which certain size particles move would already be known.

The tractive force method determines only the competence of a stream. Numerous models are available, with varying degrees of sophistication, which predict the sediment capacity at different streamflows. Most of these models are field proven and reliable. Importantly, many of the inputs to these models are identical to those required for the Water Surface Profile Program. With a little extra field data, WSPP can be expanded to give sediment transport data, as well as the hydraulic parameters it was designed for. This would be a significant addition of information with little added field work.

CHAPTER 3: CONCLUSIONS

The use of a comprehensive in-stream flow methodology, such as the one derived in this study, can be a very powerful tool for water managers. The methodology incorporates a sensitivity for the flow requirements of a wide range of in-stream uses, and the flexibility to adjust flows to accomodate monthly or seasonal changes in flow requirements. In addition, the methodology includes an accounting for water losses, which we found to be of paramount importance if in-stream resources are to be adequately protected. The application of a water-use matrix (see Figure 5-2) gives the water manager the ability to determine the critical flow requirement for a certain time period, and of interpreting the consequences of reserving an insufficient flow.

The combined use of multiple transect analysis and flow criteria for selected indicator species can be a highly effective means of determining minimum and optimum streamflow requirements for fisheries. However, using the optimum flow as a basis for determining the minimum or base flow, for a given biological system is invalid and should be discontinued. The optimum flow has no direct bearing on the minimum streamflow requirement. Imposing a relationship where none exists seriously erodes the scientific objectivity of the method and the resultant recommendations. Base flow should be defined as that discharge which first provides some increment of preferred hydrologic area over the critical region. This definition allows a quantitative determination of the minimum flow requirement.

We have shown that the flow recommendation procedure under the original methodological framework (percent of optimum flow) did not meet the criteria of water applicability. Under the original minimum flow definition, the recommended rearing flow for the Tongue River would be about 9.0 cms. The natural streamflow was less than 9.0 cms. about 60% of the time in the period 1961-1970. Using the base flow definition, the minimum flow requirement is 3.70 cms. This flow was equalled or exceeded 73% of the time from 1961 to 1970, and meets the criteria of water availability better than the original definition. Also, it is more realistic to compare spawning flows with monthly streamflow probabilities than with the annual flow duration curve. The base spawning flow of 18.0 cms. for the Tongue River is normally exceeded 83% of the time, based on streamflow records for June, from 1961 through 1974. The advantage of the base flow concept to the water manager or reserving agency, is that it defines a "fall back" position in water negotiation situations. It therefore provides the manager a base line from which negotiations may be made upward, but not downward without serious consequences.

The field tests conducted in this study give credence to both the concepts of optimum flow and base flow. As base flow is approached, it might be expected that the diversity and productivity would begin to decline. Indeed, these were the findings of the field tests. Once base flow is passed, the decline in diversity and productivity may become precipitous. The field tests did not apply directly to spawning flow requirements, nor to longterm trends within the fishery. Both of these subjects need to be field tested, preferably over a number of years.

The formulation of flow criteria for warm water streams has only begun with this project. It is extremely difficult to select an ideal indicator species when the preferred hydrologic conditions and ranges of tolerance have not been determined for most of the species in prairie rivers. This is particularly true for the determination of spawning flow criteria. Future research into flow criteria should devote a considerable effort in this area.

An ideal indicator species should be velocity limited, as velocity is affected more by reduced discharge than is depth. For this reason we conclude that Rhithrogena would be a better rearing indicator in the Tongue River than would the stonecat. Indeed, it was shown that base flow for aquatic insects was about 0.85 cms. higher than for the stonecat. The shovelnose sturgeon appears to be an excellent spawning indicator for the intermediate part of the spring runoff. Other species, however, such as the sauger and channel catfish, should be re-investigated for use as mid-spring and early summer spawning indicators, respectively.

A frequent criticism of the multiple transect method of assessing optimum or base level streamflow requirements, is that it is time consuming and expensive. The time requirement for data collection and drawing hydrologic maps is about 3 man-days for each section and discharge measured and mapped. An additional time requirement occurs as a result of waiting for the discharge to change sufficiently to warrant re-mapping a section. Chapter 6 shows how the use of flow prediction models can significantly reduce the time, and consequently the cost of multiple transect analysis. With the use of a computerized contour plotter, the total time requirement from initiation of data collection to receiving the completed maps may be reduced as much as 95 percent.

Both the Water Surface Profile Program and the CONTOUR Program were shown to give reliable results. The time requirements for both programs are about the same, approximately 2 to 3 man-days per section. In view of the type of data output, and the overall superiority of hydrologic mapping to single transect analysis or other flow assessment techniques, it must be concluded that the use of flow prediction models is a significant improvement over conventional methods.

A second criticism of the multiple transect methodology is that it is only applicable in small, wadeable rivers. This criticism is totally unjustified. Data collection consists almost exclusively of current meter measurements. For years the U.S. Geological Survey has made similar measurements from boats mounted with cable booms, winches, and bomb weights. There is no reason that the same equipment would not work for hydrologic mapping on large rivers. Even the cumbersome tagline may be eliminated, if desired, with the use of electronic distance meters.

Reproducibility of the methodology may be seriously affected if several precautions are not observed during site selection and field installation. Critical areas for rearing should be encompassed in the controls, and measured at approximate right angles to the channel. Areas with shelves, bars, and islands should be avoided. Critical areas for spawning should include gravel bars and shoals, which are usually the preferred spawning locations for many mainstream fishes. At least one transect should be placed above the control, and data from this transect used to make any discharge calculations. Finally, at least five discharges should be mapped to determine either the optimum or base flows. Reproducibility and reliability are enhanced as more discharges are mapped, but the increase in accuracy must be weighed against the effort of attainment.

Studies of ice formation in the Tongue River indicate that reduced discharge would result in a thicker surface ice sheet than normal. Two distinct flow requirements are involved in ice considerations: 1) the requirement to prevent excessive icing of riffle areas; and 2) the requirement to prevent ice jams when the spring break-up occurs. At the rearing base flow of 3.70 cms., up to 60% of the riffle area may be frozen solid. However, all this area is not really lost, as much of the riffle area will not meet criteria at base flow. At flows less than base flow, 80% to 90% of the riffle areas may be lost to ice, with a potential for loss of circulation and winterkill in downstream areas.

Serious ice jamming can be prevented with flows of 18.0 to 20.0 cms., but may be mitigated by flows as low as 10.0 cms. Ice jams are virtually assured at flows less than 6.0 cms. It must be concluded, therefore, that ice formation will not be an over-riding consideration at flows above the base flow. Passage requirements for the break-up period over-ride the base flow level by a rather large margin.

Thermodynamic models to predict the equilibrium thickness of the ice sheet may prove to be extremely useful tools in the future. At this time, more research is required to determine the heat production rate of running water, the relationship between ice thickness, bed roughness and velocity, and their affect on the rate of growth of the ice sheet.

Unlike most other in-stream uses of water, which tend to be complementary, streamflow for riparian vegetation is additive in the Tongue River. It is the only comsumptive in-stream flow requirement. The highest rates of water use occur during June, July, and August. As a result of the water supply mechanism for the trees, the effects of the vegetation on streamflow would be a more serious problem than the effects of streamflow on the vegetation. If there is any water in the river, it is probably available to the trees.

The mean daily instantaneous flow requirement for riparian vegetation, excluding irrigated cropland, was calculated to be 1.54 cms. for a rain-free month of July. The maximum daily rate of withdrawal may be as high as 1.94 cms. for several hours per day during July. The mean daily July (rain free) requirement for irrigation is around 8.0 cms.

If only the rearing base flow were released from the Tongue River dam, it is apparent that it would quickly be depleted. In fact, if only an irrigation flow of 6.67 cms. were released, and riparian losses not considered, the lower 155 km. of river would fall below the base flow level, and the lower 50 km. would probably have zero discharge. Therefore, it must be concluded that riparian consumptive losses must be calculated separately and added to the base fishery requirement to ensure sufficient water for both.

The Penman equation used to estimate the mean daily and maximum daily evapotranspiration rates appears to give satisfactory results. The estimation of evapotranspiration by the Penman equation is probably as reliable, and much easier and quicker, than an empirical determination. The source of greatest error on any determination of this type is the estimation of the area of canopy cover on the floodplain. The use of aerial photos is probably the only satisfactory method of making this estimation. However, estimates made from aerial photographs should be checked against ground truth data to determine their accuracy.

The transport of sediment, and flow requirements for pool scouring are complementary uses to spawning flows. Most of the sediment entering the Tongue River from its tributaries is so fine that it passes through the system as predominately suspended load. The primary source of large size sediment, outside the channel itself, is from slumping and caving from the numerous stream-cut terraces along the river. Pool scour was estimated to begin at around 18.0 cms.; however, the rate of sediment removal at this flow is so slow that the discharge would need to be maintained for a long period of time for effective scouring to take place. A flow of 25.0 to 30.0 cms. would more efficiently remove the sediment, using less total water by comparison, and would provide much better spawning flows.

Sediment transport models can be useful tools in assessing streamflow requirements. However, some of the inputs to the models may be difficult to obtain in the field. For many models, however, the necessary data are very similar to those required for the Water Surface Profile Program. With a little extra effort in data collection, a vast amount of information on sediment transport may be obtained in the course of applying a flow prediction model.

CHAPTER 4: RECOMMENDATIONS

The Indicator Species-Critical Area method for determining in-stream values was found to meet the three criteria for validity: accuracy, ground truth, and water availability. However, several procedural and methodological changes were required before these criteria were met. Recommended modifications to the methodology are as follows:

1. The determination of a minimum streamflow requirement as a percentage of the optimum flow should be replaced by the base flow concept as defined in this study.
2. For at least some part of the year, aquatic insects appear to be more sensitive to reduced streamflow than do fish. Therefore, if food is potentially limiting, the invertebrate fauna should be included in any in-stream flow considerations.
3. The shovelnose sturgeon appears to be an excellent midseason spawning indicator. However, indicators for earlier and later spawning periods should be investigated and flow criteria determined. The sauger, smallmouth bass, and channel catfish are suggested as potential spawning indicators.
4. Critical areas for rearing should be selected according to the following criteria:
    a. The area should contain a substrate of smooth and angular medium cobble (128 to 256 mm. median diameter). If such substrates are not available, the researcher should find conditions that most closely approximate a cobble substrate.
    b. The riffle area should form a complete control across the entire channel, at approximately a right angle to the flow.

c. River reaches containing shelves and bars should not be used as critical areas, unless a separate substrate map is used in compilation of the composite map. Areas with large islands should not be used at all because the control is likely to be at different positions on either side of the island.

d. Critical areas for spawning should include gravel bars and shoals. Channel constrictions and scour pools associated with mid-stream bars should not be considered part of the critical area, although they will frequently meet flow criteria for the indicator species. These areas are not very sensitive to changes in discharge, and maintain a fairly consistent hydrologic character even at low flows.

5. At least one transect should be placed above the control at the critical area. Data from this transect should be used to make any required discharge calculations.

6. A minimum of five discharges should be mapped at each critical area to define either the optimum or base flow, but not both. Seven to ten discharge measurements are probably sufficient to determine both the optimum and base flow. Inas much as hydrologic contour maps compiled for each critical area may be used to assess other in-stream flow functions, such as ice formation, all mapped discharges should be considered necessarily worthwhile.

7. The use of flow prediction models, particularly those outlined in this study, is highly recommended. The Water Surface Profile Program is particularly useful in that hydraulic functions other than flow characteristics (i.e. tractive force, sediment transport, etc.) may be determined from WSPP data. The CONTOUR Program may be implemented concur-

> rently with the WSPP. It was shown that, in particular, velocity data from CONTOUR is equal or superior to that from the WSPP and is more readily applied to hydrologic mapping. However, caution is advised in the use of the CONTOUR model for extrapolation. The model is designed as an interpolative tool, and extrapolation beyond the field measured end points is unwarranted.

There are several in-stream uses of water which periodically over-ride the requirements of the fishery, or are supplementary to them. It is, therefore, recommended that any intensive level methodology should include these considerations, which is not as difficult as it might appear. Hydrologic maps can be used to determine the extent of riffle icing at various flows, and passage requirements for break-up. Determination of riparian vegetation requirements involves considerable work, but this determination is so essential that the effort is entirely justified. Sediment transport rates may be adequately described by one of a number of mathematical models available. The inputs to the models are similar to those of the WSPP Program. Additional field data would include an analysis of the bed materials, obtained by pipe or auger sampling, and temperature and water density data. These data could easily be obtained in the course of applying a WSPP-CONTOUR modeling program to a critical area. It is recommended that these collections be made as a routine procedure in the application of flow prediction models.

Water quality problems are likely to change from basin to basin, depending on land use, population, and industrial development. Specific water quality models should be implemented as the need, or the prospective need, arises. Again, the hydrologic information generated from the flow prediction models can be extremely useful in the application of these models. Other data, such as BOD loading or salinity concentrations are often quite easy to obtain.

It is further recommended that in-stream flow requirements be determined for each week, month, or season, depending on the over-riding consideration for that particular period. For example, a higher discharge is needed in late February in the Tongue River to minimize ice jams, but a rearing base flow is probably adequate from October through February. Spawning flows should be based on an appropriate indicator species for early spring, mid to late spring, and early summer respectively. Fall spawners may also be a matter for consideration. Riparian vegetation and irrigation requirements should be considered additive and determined on a monthly basis. Discharge requirements for sediment transport and pool scouring should not be set at the lowest discharge at which a certain particle size commences to move. Nor should it be set at the highest rate-shortest period flow to maximize the efficiency of water use. A reasonable balance can be maintained between sediment removal rates and the spawning requirements for a particular spawning indicator.

A flow recommendation derived from any methodology should be checked against the flow duration curve (or monthly probability curve in the case of spawning flows) to ensure that the criteria for water availability can reasonably be met. However, the flow duration curve alone should not be the sole basis for determining an in-stream flow requirement. In addition to its essentially subjective elements, the flow duration curve itself may be biased by diversions, or seasonal water losses, above the gaging station. A situation similar to this exists on the lower Tongue River where a large diversion removes a substantial flow above the gage house. While there is a good fishery in this portion of river, the fish have the option of retreating to the Yellowstone River when flows become too low. This option is not reflected in the flow duration curve, nor is it acknowledged by any methodology using streamflow records alone, If the fishery were isolated, it might become apparent that the natural streamflow is below base flow for parts of the summer.

Research Needs

The most pressing research requirement is the further compilation of flow criteria for key species in warm-water streams. This is especially true for spawning criteria. Investigations of spawning criteria should not only include specific depth, velocity, and substrate details, but also possible important spawning conditions, such as temperature, turbidity, photoperiod, rise in stage,and bed movement. The criteria developed for the shovelnose sturgeon in this study is to be considered only tentative. Spawning, and spawning habitat should be monitored for several years, and cross-checked with year-class strength to determine spawning success. Ideally, flow criteria for spawning should perhaps be based on success rather than activity.

Research should also be initiated into the comprehensive use of computers and computer plotters for compiling data and plotting hydrologic contour maps. The primary reason that the multiple transect method is not more widely used is because of the large time and manpower requirements involved in its application. If the time requirement can be reduced, the methodology is likely to be more widely applied. The use of flow prediction models and computer plotters may reduce the time requirements to as little as one-fifth to one-tenth current practice.

The critical area-indicator species methodology should be applied to a large river, such as the Yellowstone, using boats and boat-mounted stream gaging equipment. It has apparently been assumed that the methodology is only applicable to small rivers, but this assumption has been neither proved nor disproved by an actual field test. The use of an electronic distance meter to replace the conventional tag-line, is strongly recommended for large river work.

A long-term (3 to 5 year) field test of the critical area-indicator species methodology is also needed. The field tests conducted in this study were necessarily short term. A long-term test should cover an extended length of river, and should include virtually every habitat type and fish in the river. Such a field test should monitor essentially the same things studied in this project, but under a controlled-flow, experimental situation. Incremental flow analysis using controlled reservoir releases would be one means of better implementing such a study.

The entire subject of over-winter behavior of aquatic insects, especially in streams subject to surface ice formation, is a virtual unknown. Research should be conducted to determine the movement and activity of aquatic invertebrates during the surface ice season, and the effects of spring break-up on the productivity of riffle areas. Ice research should also investigate the hypothesis that frictional heat from running water retards or prevents the thickening of the ice sheet. A related problem is the determination of the heat exchange rate from water to ice.

CHAPTER 5: A COMPREHENSIVE METHODOLOGY FOR IN-STREAM FLOW DETERMINATIONS

Introduction

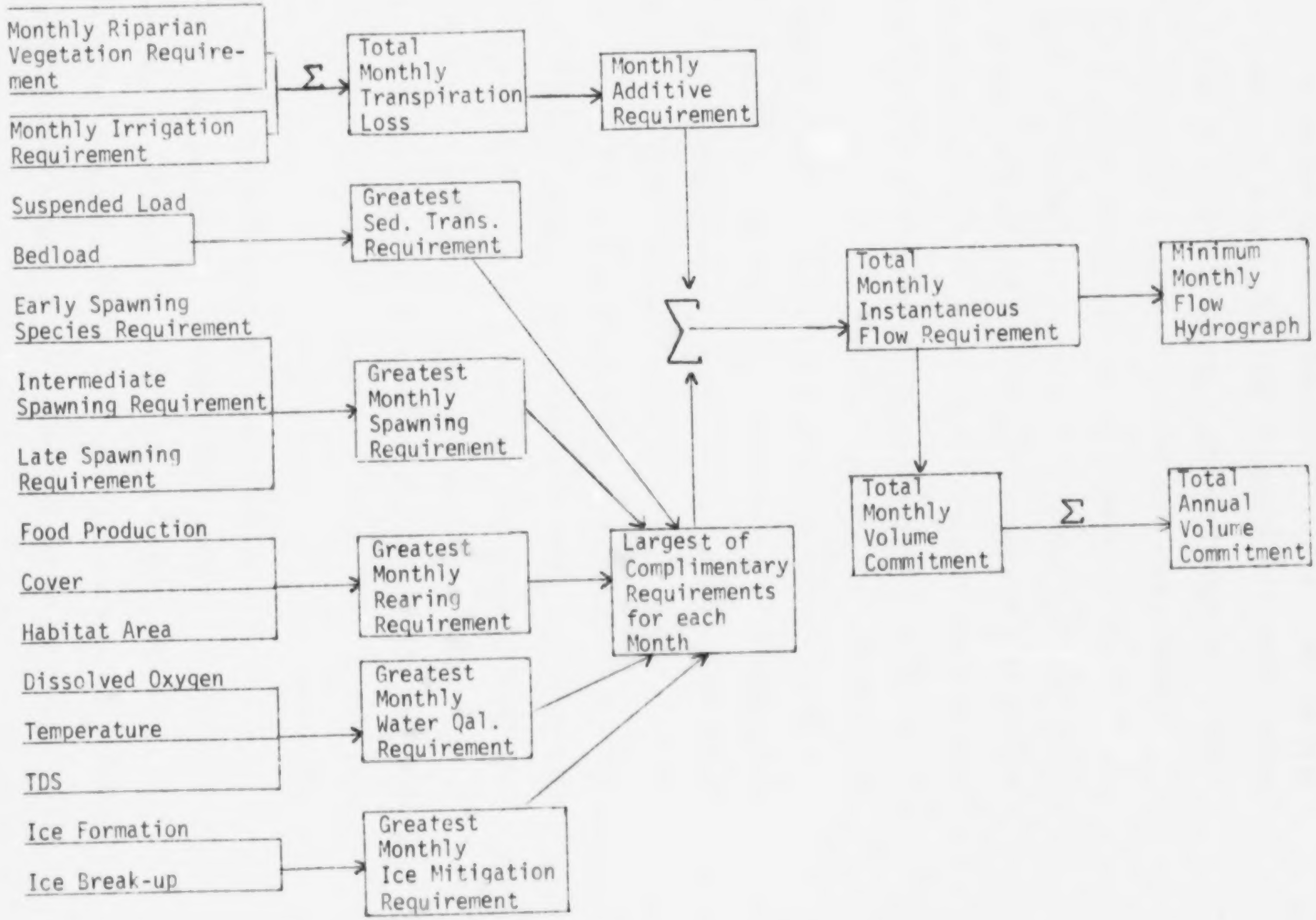
As originally conceived, an in-stream flow methodology referred primarily to a procedure designed to assess streamflow as a primary influence on fishery resources. The assessment of the relationships of streamflow to other aquatic resources and processes was not considered a primary function of the methodology. However, several of these "secondary" streamflow functions (such as ice formation or sediment transport) have direct impacts on the fishery, or on the river itself. As this study progressed, it became apparent that the consideration of these functions should actually be incorporated into a methodological framework.

Presently, there is no single procedure capable of simultaneously determining the minimum streamflow requirements of several related aquatic resources. Rather, the flow relationships and requirement for each type of resource, or problem area, must be determined separately. Comparisons between the flow requirements for different ecosystem components can give a better understanding of the total flow requirements of the ecosystem.

Thus, an "In-stream Flow Methodology" should be conceptualized as the end result of the application of several problem-specific, component methodologies. Figure 5-1 is a simplified flow chart describing the combination of the components under a single methodological framework.

Streamflow requirements for each of the components of Figure 5-1 may be determined independently, using a methodology designed to assess each requirement. Some of the in-stream water uses are considered complementary;

Figure 5-1: Component diagram of a comprehensive in-stream flow recommendation procedure. Components at the far left of flow diagram refer to minimum flow requirements for each component. For some months, certain components go to zero.


Monthly Riparian Vegetation Requirement
Monthly Irrigation Requirement
Σ
Total Monthly Transpiration Loss
Monthly Additive Requirement
Suspended Load
Bedload
Greatest Sed. Trans. Requirement
Early Spawning Species Requirement
Intermediate Spawning Requirement
Late Spawning Requirement
Greatest Monthly Spawning Requirement
Food Production
Cover
Habitat Area
Greatest Monthly Rearing Requirement
Dissolved Oxygen
Temperature
TDS
Greatest Monthly Water Qal. Requirement
Ice Formation
Ice Break-up
Greatest Monthly Ice Mitigation Requirement
Largest of Complimentary Requirements for each Month
Σ
Total Monthly Instantaneous Flow Requirement
Minimum Monthly Flow Hydrograph
Total Monthly Volume Commitment
Σ
Total Annual Volume Commitment

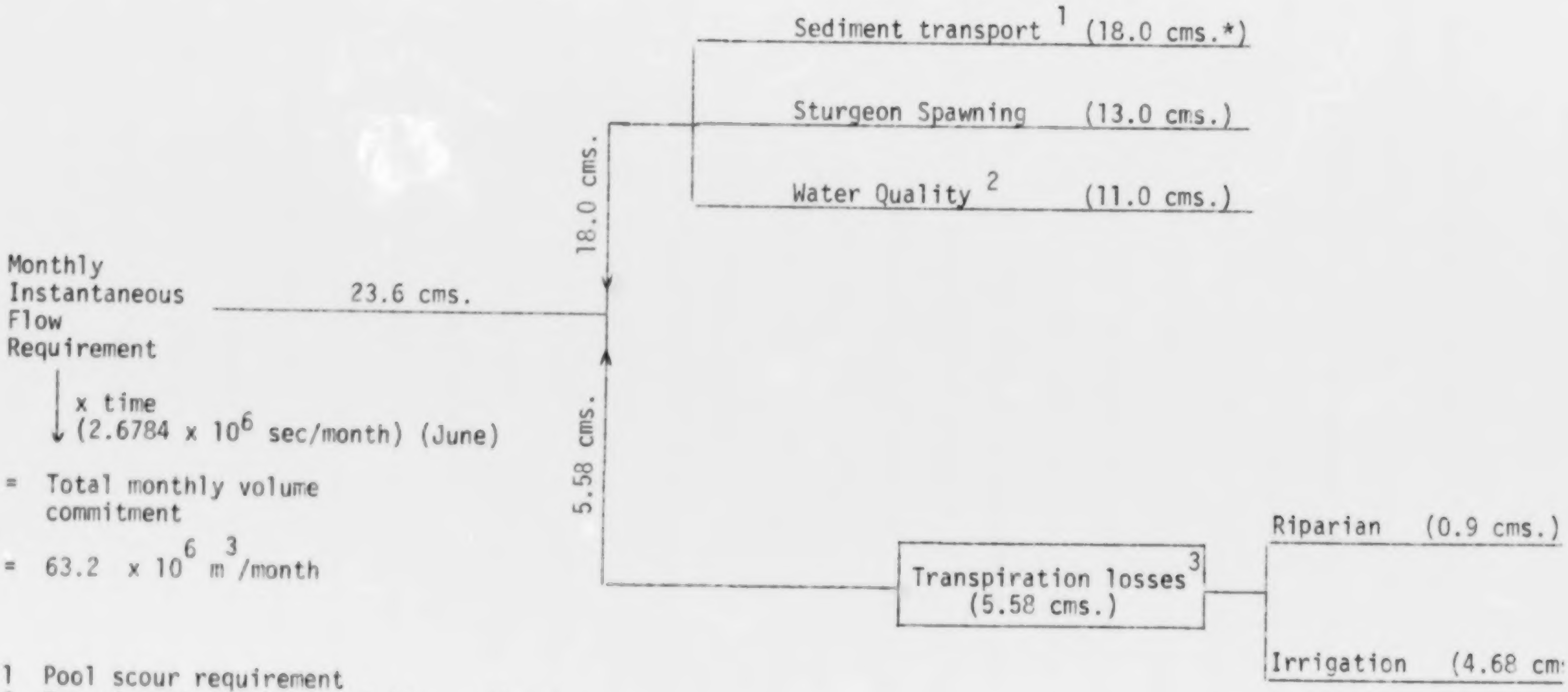
that is, the streamflow requirement to satisfy one use may satisfy several others. Under this framework, the complementary in-stream use with the highest flow requirement for a certain time period is considered critical.

However, consumptive water uses such as transpiration from riparian vegetation and irrigated crops, are considered additive or supplementary uses. Flow requirements for these uses are combined and added to the critical flow requirement as determined for the complementary uses. The total in-stream flow requirement for any time period is then defined as the summation of the additive requirements and the greatest complementary requirements.

The use of the comprehensive methodology to make a minimum streamflow recommendation is illustrated by the flow diagram in Figure 5-2. In this Tongue River example the flow requirement for pool scour is 18.0 m^3/sec., while the minimum flow for sturgeon spawning is 13.0 m^3/sec. The flow required to flush fines from gravel areas is only 11.0 m^3/sec. Thus, critical streamflow requirement for all complementary uses is 18.0 m^3/sec. Total transpiration losses were calculated to be 5.58 m^3/sec. Therefore, the total in-stream commitment for June is 23.6 m^3/sec. This is the instantaneous flow requirement to be released at the Tongue River Dam. A release less than this may result in inadequate spawning and scouring flows in the lower river.

In as much as different water requirements assume greater or lesser importance at different times of the year, this methodological concept allows the flexibility to adjust flow recommendations to meet the most important seasonal or monthly need. A second attractive feature of this method is that it also allows the flexibility to plan for changes in land use or

Figure 5-2: Example of integrated methodology used to determine the minimum streamflow requirement for the Tongue River during the month of June.


Monthly Instantaneous Flow Requirement
23.6 cms.
x time (2.6784 x 10^6 sec/month) (June)
= Total monthly volume commitment
= 63.2 x 10^6 m^3/month
18.0 cms.
5.58 cms.
Sediment transport 1 (18.0 cms.*)
Sturgeon Spawning (13.0 cms.)
Water Quality 2 (11.0 cms.)
Transpiration losses 3 (5.58 cms.)
Riparian (0.9 cms.)
Irrigation (4.68 cm

1 Pool scour requirement
2 Entrainment dishcarge of fine sediment
3 Corrected for rainfall
* cms. = cubic meters per second

waste loading, which might require a larger instream flow to maintain water quality or other in-stream values. Additionally, the methodology incorporates the analysis of monthly variable water losses. Failure to correct the total in-stream flow requirement for these losses will result in less than adequate flow for the complementary in-stream uses. Application of such a comprehensive methodology will provide a more powerful management tool than relying on a piecemeal approach to in-stream flow recommendations.

It should be apparent that the reliability of the comprehensive in-stream flow recommendation depends upon the reliability of each component methodology. A brief description of each of the component methodologies is provided below. The water quality component was not included in this study due to constraints of manpower; however, descriptions of water quality methodologies will be mentioned briefly.

Water Quality Component

Models applicable to the determination of flow requirements to maintain water quality may be found in general santiary engineering texts, such as Velz (1970), or in technical bulletins outlining specific water quality (WQ) parameters. Some water quality considerations are relatively more important during certain seasons or months. For example, dissolved oxygen is likely to be a most important parameter during the summer, when water temperatures are highest, and during the fall, when there is the greatest amount of accumulated vegetation and detritus in the stream. The importance of other WQ parameters will vary from stream to stream, depending on geology, land use and effluent character. The concentration of total dissolved solids, sodium, and boron are of prime importance in a stream used for irrigation as opposed to one which is not. Therefore, it becomes important to identify those WQ parameters which are most critical to a particular stream, and to determine the streamflow requirements to maintain a desired level of water quality, based on the critical time period for each WQ parameter.

Mathematical modeling is usually employed in the assessment of streamflow requirements to maintain water quality. Several types of WQ models are given below:

Dissolved Oxygen:

The most commonly used model for predicting streamflow and waste loading effects on dissolved oxygen content is the Streeter-Phelps carbonaceous decay model. The generalized form is given in Equation 5-1.

$$\frac{\partial C}{\partial t} = \frac{-1}{A} \frac{\partial}{\partial x} (QC) - K_d L - K_n L_n + K_a (C_s - C) - S_b + P - R + C_r \left[\frac{\partial Q}{\partial x} / A \right] \qquad \text{(Eq. 5-1)}$$

Where,

C = dissolved oxygen concentration

C_s = dissolved oxygen concentration at saturation

C_r = dissolved oxygen added along river

S_b = dissolved oxygen sink due to sludge deposition

P = dissolved oxygen added by photosynthesis

R = dissolved oxygen sink due to plant respiration

K_a = reaeration coefficient

K_d = deoxygenation coefficient for carbonaceous waste

K_n = deoxygenation coefficient for nitrogenous waste

A = average cross-sectional area of reach

Q = stream discharge

L = waste loading in mg/L

X = distance

Implementation of Equation 5-1 requires the determination from the literature of appropriate coefficients, and the empirical determination of most of the other inputs. Details of the Streeter-Phelps model may be found in Velz (1970) or numerous references listed by Stalnaker and Arnette (1976).

Temperature:

The effect of reduced streamflow on extreme summer water temperature may be assessed through the use of an energy budget model. The temperature determination of a discrete volume of water as it moves downstream is based on the method derived by Raphael (1962). This method consists of calculating the heat content of the water body, and converting this heat content to a temperature. Equation 5-2 shows the conversion process.

$$\triangle t_w = \frac{1}{V_i}\left[\frac{H_t A \theta}{w} + V_{ij}(t_{ij} - t_w)\right] \qquad \text{(Eq. 5-2)}$$

Where,

$\triangle t_w$ = change in temperature, in time θ, ^{o}C

V_i = total flow volume, in some time interval, θ (m^3)

A = surface area of the volume (m^2)

H_t = increase in stored energy ($Kcal/m^2/hour$)

θ = time in hours

w = specific weight of water (Kg/m^3)

V_{ij} = inflow volume in time interval θ (m^3)

t_{ij} = temperature of inflow volume (^{o}C)

t_w = initial temperature of water volume (^{o}C)

The value of the increase in stored energy, H_t, is calculated using the energy balance equation:

$$H_t = (H_s - H_r) - H_b - H_e \pm H_h \qquad \text{(Eq. 5-3)}$$

Where,

H_t = increase in stored energy as above

H_s = incoming solar radiation

H_r = reflected radiation from water surface

H_b = effective back radiation

H_e = energy loss to evaporation

H_h = conducted heat loss

The units of all these terms are Kcal/m^2/hour. Inputs for the determination of H_t may be determined from local climatological data and any of several specific references (Velz, 1970; Raphael, 1962).

Total Dissolved Solids or Discrete Salts:

For conservative contaminants, such as total dissolved solids (TDS), it is assumed that dilution is the only mechanism for reducing the concentration. Natural sources to TDS include feeder streams or groundwater inflow. Increased concentration of TDS may occur as a result of removing water from a stream which receives high concentrations of dissolved solids from these sources. High concentrations of TDS may also be caused by increased evaporation of the natural stream due to increased travel time resulting from reduced discharge. The dilution equation (Crutchfield, et. al. 1975) is given below.

$$C_{Mi} = \frac{Q_w C_{wi} + Q_r C_{ri}}{(Q_w + Q_r)} \qquad \text{(Eq. 5-4)}$$

Where,

C_{Mi} = the resultant concentration of the influent and receiving water mixture (mg/l)

Q_w = the flow rate of the influent water (m^3/sec)

Q_r = the flow rate of the receiving water (m^3/sec)

C_{wi} = the concentration of the dissolved solid parameter (mg/l) in the influent water

C_{ri} = the concentration of the dissolved solid parameter in the receiving water (mg/l)

Fisheries Component

The methodology used to determine minimum streamflow for fisheries is designated the Critical Area-Indicator Species Method. This method utilizes the environmental alteration of shallow water riffles and gravel bars in response to changes in streamflow. These habitat areas reflect a greater degree of sensitivity to change than other in-stream habitats, because of the rapid change in hydrologic variables with change in discharge. The sensitive habitats are defined then, as critical areas.

A logical extension of the critical area concept is that organisms which inhabit or utilize these shallow water areas will necessarily be more sensitive to changes in streamflow than inhabitants of other stream areas. Therefore, if suitable habitat is maintained in the critical area for species using that area, it is assumed that conditions will be suitable for all other species in the river. This concept is used in the criteria defining an indicator species.

In applying this methodology, the same indicator species is not used throughout the year. Rather, several indicator species have been identified for use during the migration and spawning phase of the life history, and others during the rearing phase. For the purposes of this study, the sauger and shovelnose sturgeon were selected as migration and spawning indicators. Rearing conditions were evaluated in terms of productivity (aquatic insect habitat) and balance (habitat diversity for fish). Maximum biomass and diversity were utilized as criteria for maximum productivity. The stonecat was used as the indicator species delineating critical area habitats.

This method involves two separate phases of field data collection. The first phase is the formulation of flow criteria for each indicator species. This flow criteria includes a determination of the velocity range, depth range, and bottom type most commonly associated with each indicator species.

The second phase evaluates a series of discharges across a critical area, or areas. This evaluation process requires the construction of planimetric hydrologic contour maps which delineate areas of equal depth or velocity. Field data for the maps are collected from four or more transects across a critical area. At specified intervals across each transect, measurements of depth, velocity, and bottom type are made. A depth contour map is prepared by transferring the transect depth measurements to their appropriate positions on a scale drawing of the channel. Lines of equal depth are then drawn on the map by interpolating to the desired depth contour between points on the same transect, or between corresponding points between transects. Figure 5-3 shows a sample of a depth contour map with the field data indicated on the transect lines. Velocity maps are similarly constructed on a separate planimetric map. These maps may be interpreted in a manner similar to reading a topographic map.

The adequacy with which a given discharge provides habitat over the critical area for the indicator species may then be evaluated with the use of a

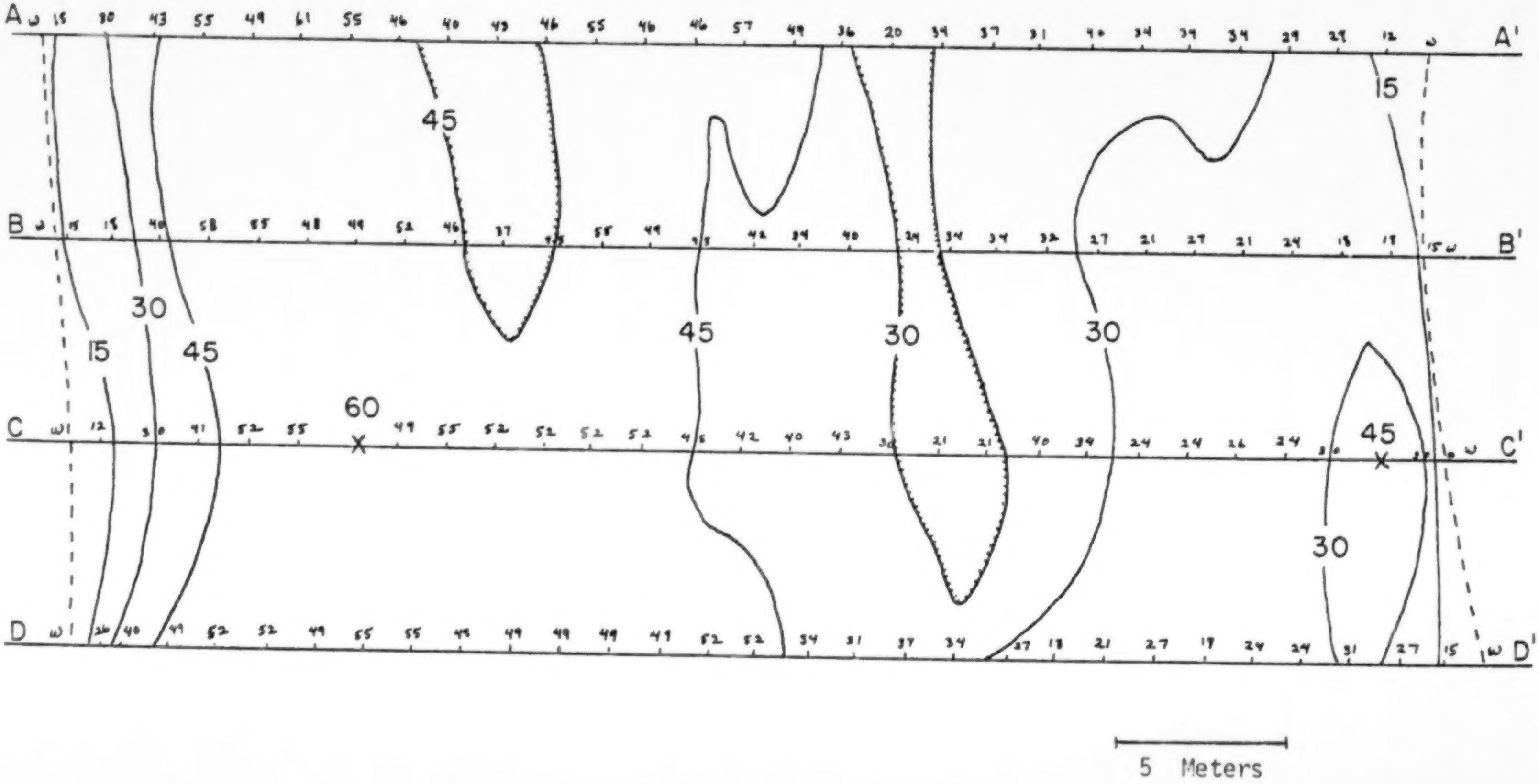


Figure 5-3: Example of the construction of a depth contour map. Handwritten numerals are from field data; isolines of equal depth drawn by interpolation between data points; depths are in cm.

composite map. These maps are constructed by superimposing the appropriate depth, velocity, and bottom type contours on the same map. Only the contours delineating the boundary conditions for the flow criteria of a given indicator species are indicated. Areas of the map which do not meet depth, velocity, and bottom type criteria are then cross-hatched. Unmarked areas remaining on the composite map meet all of the flow criteria for the indicator species. These areas are measured with a planimeter, and the total area meeting the flow criteria determined for each discharge. For each discharge "mapped", the area meeting the flow criteria is then plotted against discharge. This curve is used to determine the optimum and minimum streamflow requirements for the indicator species. An example of a composite map is given in Figure 5-4. Figure 5-5 shows a plot of preferred habitat area vs. discharge.

Ice Formation Component

At the outset of this study, it was recognized that ice formation played an important role in NGP streams, but the extent and nature of its influence was not known. The results of the study show that ice formation effects the river ecosystem in two ways: 1) by reducing the amount of habitable area, and 2) by disturbance of the river bed during the break-up period.

We found that the equilibrium ice thickness (the thickness at which heat loss from the top of the ice sheet equals the heat gained at the water-ice interface) was inversely related to water velocity. Therefore, slower water velocities were invariably associated with a thicker surface ice sheet. In as much as water velocity decreases significantly with reduced discharge, a decrease in discharge would result in a greater equilibrium ice thickness.

The extent of habitat loss to the formation and thickening of an ice sheet

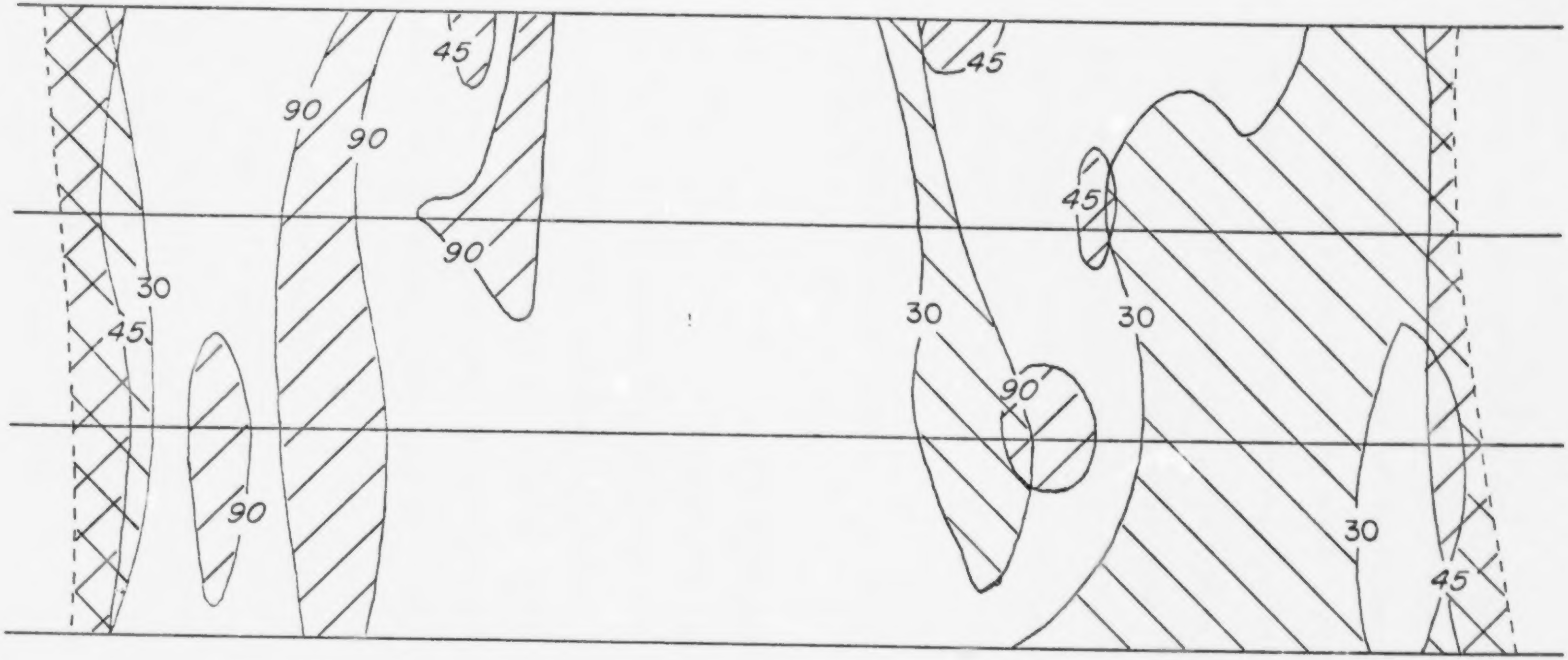


Figure 5-4: Example of a composite map, showing areas meeting flow criteria for the stonecat. Area with no cross hatching meets all criteria.

Total area meeting criteria: 425 m^2.

Discharge = 12.0 cms.

5 Meters

▧ Area not meeting depth criteria

▨ Area not meeting velocity criteria

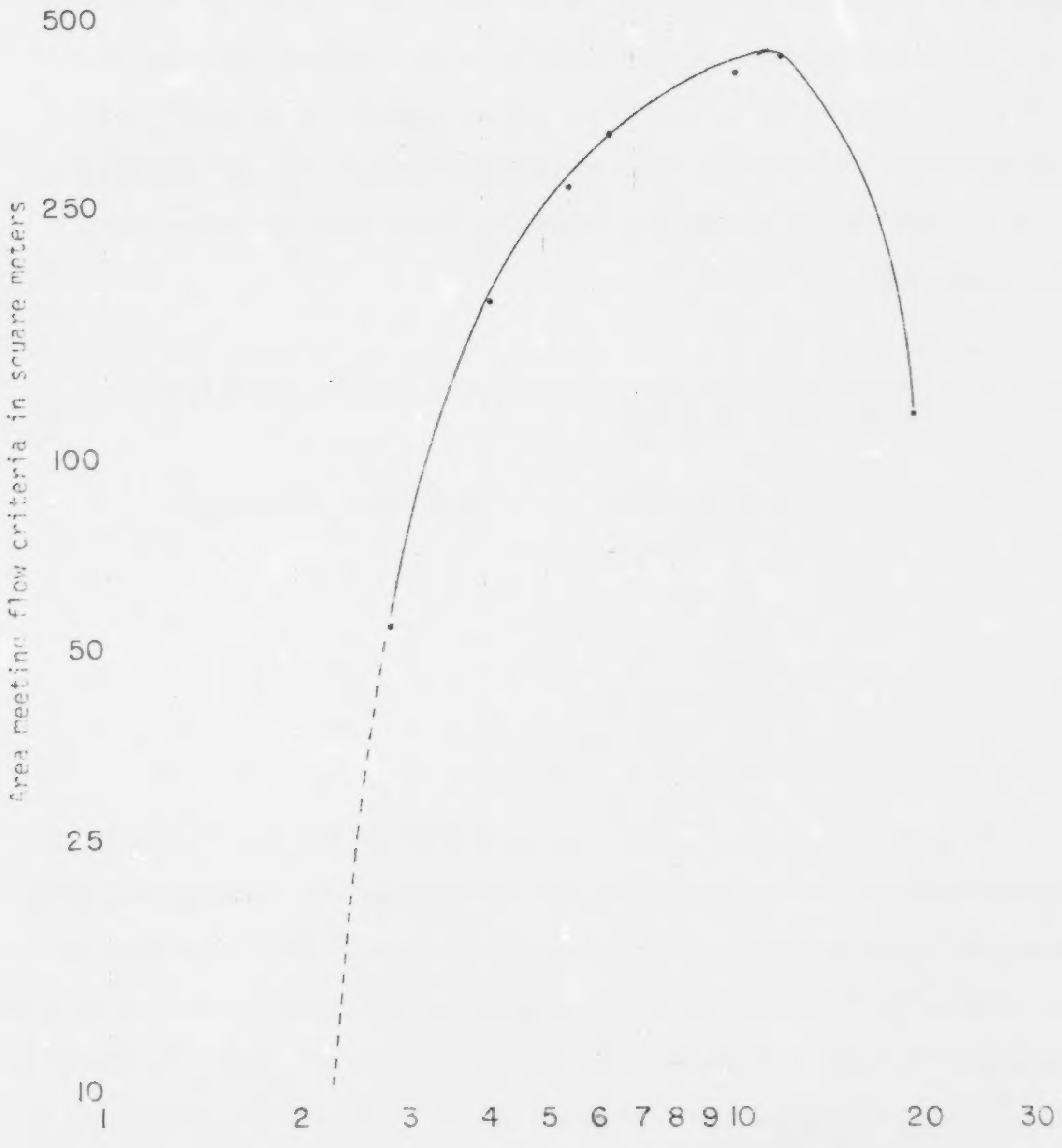


Figure 5-5: Example of preferred area vs. discharge, or "peak of the curve" plot used to determine optimum and minimum streamflow requirements.

depends not only on the discharge, but on the thermal regime of the region. At this time, the relationship between ice thickness and current velocity can best be determined empirically, although several thermodynamic models capable of predicting equilibrium ice thickness may soon become practical.

The methodology used in this study to assess the area loss due to ice utilizes an empirically derived relationship between ice thickness and current velocity. For a given range of velocities there is a corresponding range of expected ice thickness. Table 5-1 illustrates the relationship described above.

Table 5-1: Expected ice thickness derived from current velocities at measurement locations.

Current velocity cm./sec.	Equilibrium thickness cm.
60	19
50	21
45	21
40	22
30	25
20	29

The extent of habitat loss may be evaluated for the same critical areas used in rearing flow determinations, using the depth and velocity contour maps prepared for those areas. Velocity contour lines are used to estimate the approximate thickness of the ice. The expected thickness of ice is then superimposed on the depth contour map for the same discharge. Where the predicted ice thickness is greater than, or equal to, the depth within a given contour interval the area is assumed frozen to the bed. The percentage of the riffle lost to ice formation may then be calculated from the maps.

The determination of flow requirements to prevent ice jams from developing involves a much more direct procedure. Since the greatest thickness of ice measured in the Tongue River over the last two years (1975, 1976) was not much more than 30 cm., it was assumed that most of the ice released from pool areas would be about 30 cm. thick. The depth contour maps for a given critical area were then examined to determine the extent of the area less than 30 cm. in depth at various discharges. If the depth over the entire critical area is greater than the thickness of the ice floating through the area, the chance of ice jam formation is decreased considerably. Conversely, the probability of a serious ice jam forming over a critical area increases as the area containing the required depth decreases.

Transpiration Loss Component

Since transpiration losses along a river are additive, it is not possible to select a critical area for the determination of the transpiration flow requirement. The methodology used to determine transpiration losses is essentially the same for riparian vegetation and irrigated cropland.

The first step, in either case, is the determination of the total canopy cover involved in the transpiration process. For irrigated crops, the area covered is usually available in the literature,including U.S.G.S. streamflow records and gaging station descriptions. However, the area of riparian vegetation cover must often be determined empirically. This can be accomplished with aerial photographs or LANDSAT color infrared photographs. For this study, vegetated areas were traced from aerial photos onto a gridded tracing paper, in such a manner that each small square of the grid contained some canopy. The percentage of each square covered by canopy was estimated, and that vegetation area was given a weighting factor depending on the percentage of cover. The total cover for each vegetation map prepared in this manner was determined by measuring each vegetated area with a planimeter, and multiplying by the appropriate weighting factor. Total canopy cover was determined by summation of individual canopy cover areas as determined for each map.

The transpiration rate was then determined using the Penman equation and local climatological data. By using the Penman equation, it is possible to determine the mean daily and maximum daily transpiration rates of the vegetation. These rates may be corrected for rainfall, if desired.

Daily water volume requirements for transpiration may then be determined by multiplying the total canopy cover area (in square meters) by the transpiration rate (meters per day). Instantaneous flow requirements were estimated by assuming that groundwater recharge is constant over time. By dividing the mean daily water volume requirement by 86,400 sec./day, one can estimate the instantaneous mean daily flow requirement for transpiration.

Because transpiration rates increase through early summer, and then decrease after August, the flow requirements for transpiration should be calculated on a monthly basis. Unlike many other in-stream flow requirements, for which the same volume of water may satisfy several functions, transpiration losses are consumptive. Therefore, they must be considered as an additional requirement rather than a complementary use.

Sediment Transport Component

The primary objective of the sediment transport component is to ensure that the sediment accumulated in pools is removed by a scouring flow. In this case the pools are considered critical areas. Additionally, the implementation of this methodology requires the determination of a critical stream reach, which is defined as the reach with the greatest sediment source, and the least ability to remove sediment. This reach may vary from stream to stream depending on the nature of the sediment inflow. For many streams, however, the critical reach for sediment transport will be in the lowest part of the basin, where the hydraulic gradient of the stream is at a minimum.

Sediment transport on the Tongue River was evaluated empirically by taking both bedload and suspended sediment samples at the downstream end of a large pool. Sediment rating curves for various size fractions of sediment were constructed by plotting the sediment load vs. the discharge. The interpretation of these sediment rating curves is often made more difficult by a scattering of the data points for a given discharge. This scattering phenomenon is most serious for particle sizes less than 62 microns in diameter. However, this size fraction may be omitted from the evaluation process because it does not reflect channel scour or flushing. Rather, these small particles are already in transport when they reach the lower main stem of the river. Fine to medium sand, either moving in suspension or as bedload is a better indication of the initiation of scour.

Theoretically, scour may be indicated in two ways. If the load of sediment leaving the channel section is greater than the amount entering the section, then scour may be assumed to be in progress if it can be established that sediment is not entering the channel within the section. An alternative method is the examination of the competence of the stream. This involves the determination of the discharge at which certain size fractions begin moving.

The mass balance method works well if all sediment entering the critical stream section can be measured and bank caving or slumping is not an important source of sediment in the critical stream reach. Competence is often equally difficult to determine, for some fine sand may move at virtually all discharges within the critical stream section.

The method used to evaluate sediment transport in this study is a combination of both the competence and mass balance methods. Numerous samples were taken at a relatively low flow, with no sediment entering the river from runoff. These samples were used to establish "background" levels of the load in the various size fractions of sediment. Subsequent samples at higher discharges were then examined to determine whether the load appreciably exceeded the background level. Thus, a type of cluster analysis was used to interpret the initiation of scour in the pool. For example, the background level for fine sand moving as bedload in the Tongue River section sampled was found to be about 3 metric tons per day for numerous flows below 18.0 cms. The load at 18.0 cms. varied from 4 to 5 metric tons per day. However, from 18.0 to 20.0 cms. the load increased to 10 to 12 metric tons per day. Thus, it was concluded that pool scour was initiated at around 18.0 cms. This scouring value was also indicated by other larger particle sizes moving as bedload and by the first appearance of fine sand in the suspended load.

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CHAPTER 6: IMPLEMENTATION OF THE FISHERY COMPONENT METHODOLOGY

Introduction

Essentially all of the data intensive, flow recommendation methodologies had their origins on the West Coast. Basically, each methodology utilizes extensive measurements of hydrologic parameters (velocity, depth, substrate, etc.) across single or multiple transects. Measurements are repeated for a wide variety of discharges. The adequacy with which a given discharge meets the requirements of the fishery is evaluated using comprehensive flow criteria (preferences for certain depth, velocities, etc.) for the fish species of interest. The flow which provides the greatest area of preferred hydrologic conditions is defined as the optimum streamflow.

The streams for which these methodologies were developed supported salmonid fisheries with relatively few species. Because of the popularity and high esteem of the salmonids, a considerable body of knowledge of their streamflow needs had already evolved. The development of streamflow recommendation methodologies for salmonids primary involved the coupling of the field techniques with the criteria which already existed. In addition, most salmonid streams exhibit a riffle-pool periodicity with well defined areas of microhabitat, making it relatively easy to establish study areas and evaluate the effects of different discharges on the salmonid community.

Two initial problems were defined in this study of a warm water stream in the Northern Great Plains. The first, and most serious, is the great variety of species found in the Tongue and other rivers of the region. Obviously, the formulation of flow criteria for each species was out of the question. The first problem to be resolved, then, was the species for which flow criteria should be developed.

The second problem involved the complexity of the channel in most prairie rivers. In addition to the pools and riffles common to a trout stream, the Tongue River contains waterfalls and rapids, undercut banks and backwaters both on the inside and outside of meanders, cut-off meanders, braided straight sections and braided meanders, partial riffles, channel constrictions, degrading and aggrading tributary confluences as well as other environments. Therefore, the problem of selecting the habitat type to be studied becomes important. The flow recommendation methodology proposed is designed to circumvent these major difficulties, yet provide reliable, reproducible, and defendable results.

The Critical Area-Indicator Species Method

Shallow areas in rivers, such as riffles and bars, are more drastically affected by reduced discharges than are pools, or other stream habitat areas (Kraft, 1972; Fraser, 1971). Moreover, such areas frequently retard or control the flow of water over them. The flow of water over the "control" thus affects the flow in pools, backwaters, and other areas. Gravel bars are shallow areas which may or may not act as a control; however, these areas may have special importance as spawning grounds. Due to their high sensitivity to changes in streamflow, these shallows are defined as "critical areas." The critical area concept was apparently devised independently by several different researchers, but was first promulgated by Russell and Mulvaney of Region II, USFS, (Stalnaker and Arnette, 1976).

A logical extension of the critical area concept is that the inhabitants of such shallow water areas will be more severely limited by reduced streamflow than will denizens of other habitats. Therefore, if suitable habitat is maintained for riffle dwelling species, over the critical area, then the assumption is that conditions will be suitable for all other species in the rest of the river. This concept is then used in the criteria defining an "indicator species" (Bovee, 1974).

Three separate phases of the life history of fishes are considered under the "indicator-species" methodology. These include migration, spawning, and rearing. Rearing is further subdivided into production (aquatic insects) and balance (habitat diversity) classifications.

The sauger and the shovelnose sturgeon were investigated as migration and spawning indicator species. Both species spawn in shallow, fast water and are highly migratory (Eddy and Surber, 1943; Eschmeyer, 1950; Nelson, 1968). The stonecat was selected as the indicator species for the rearing phase of life history. According to the literature, stonecats are primarily associated with riffles and rapids containing large, loose rocks (Johnson, 1965; Larimore and Smith, 1963; Clay, 1962). The stonecat is utilized primarily to evaluate fish community structure during the rearing phase. Productivity, as a function of hydrologic conditions, was evaluated in terms of macroinvertebrate biomass and diversity.

As described in Chapter 5, the Critical Area Indicator Species Method is implemented in three phases. The first phase is the determination of flow criteria for each indicator species. The second phase requires the collection of hydrologic data, including depths, velocities, and substrates over the critical area, and the construction of hydrologic parameter contour maps for each critical area and discharge studied. The final phase evaluates the adequacy with which different discharges meet the habitat requirements of a particular indicator species over the critical areas. This is accomplished through the construction of a composite map for each discharge, which delineates areas meeting the criteria developed for an indicator species, and designated as the preferred area. The discharge which provides the greatest amount of preferred area is defined as the optimum streamflow. The minimum sustaining flow as used in many methodologies, is defined as 75% of the optimum flow, the validity of this concept will be discussed in Chapter 7.

The following sections describe each of the three phases in detail, and are arranged in the same sequence as that given above.

Determination of Flow Criteria

Rearing Criteria With the Stonecat as Indicator:

Riffle utilization by stonecats in the Tongue River was examined by electrofishing from a drift boat with a 1500 watt DC mobile electrode (Vincent, 1971). Whenever a stonecat was captured, its position in the stream was marked with a small buoy. At each capture location, the parameters of depth and velocity were measured with a Price AA current meter and wading rod. Velocities were measured at 0.6 of the total depth for locations less than 60 cm. in depth. In deeper water, velocities were measured at 0.2 and 0.8 of the total depth and averaged. The bottom type was classified according to the Wentworth Particle Size Classification (Krumbein and Sloss, 1955).

Stonecats were most commonly associated with substrate particles ranging in size from small cobble to boulder, with the greatest occurrence in association with the medium cobble (128 to 256 mm.) class.

Table 6-1 shows the occurrence of stonecats with respect to depth and velocity. The mean depth of 203 stonecats collected was 45 cm., with a standard deviation of 14 cm. The mean velocity was 65 cm./sec., with a standard deviation of 20 cm./sec.

Table 6-1: Occurrance of stonecats with respect to depth and current velocity.

DEPTH (cm.)

VELOCITY (cm./sec.)	< 15	16-30	31-45	46-60	61-75	> 76
< 15	0	0	1	1	1	1
16-30	0	0	3	0	0	0
31-45	0	6	7	10	8	1
46-60	0	3	23	27	7	1
61-75	1	8	18	21	2	1
76-90	0	3	24	11	1	0
90-105	0	0	4	4	0	0
> 106	0	1	3	1	0	0

The depths and velocities outlined in Table 6-1 are suggested as flow criteria for the rearing period, as indicated by the stonecat. 78% of all stonecats were found in water depths between 30 and 60 cm.; 74% occurred where velocities ranged between 45 and 90 cm./sec.

Combining the first and last pairs of columns and rows, as suggested by Snedecor and Cochran (1967), X^2 was computed for Table 6-1. The null hypothesis is stated as: there is no significant difference in the distribution of velocity classes within depth classes of stonecats occurrence. X^2 for the condensed table (4x6) was 34.2887, with 15 d.f. The null hypothesis was rejected at the 99.5% level of significance (p = .005).

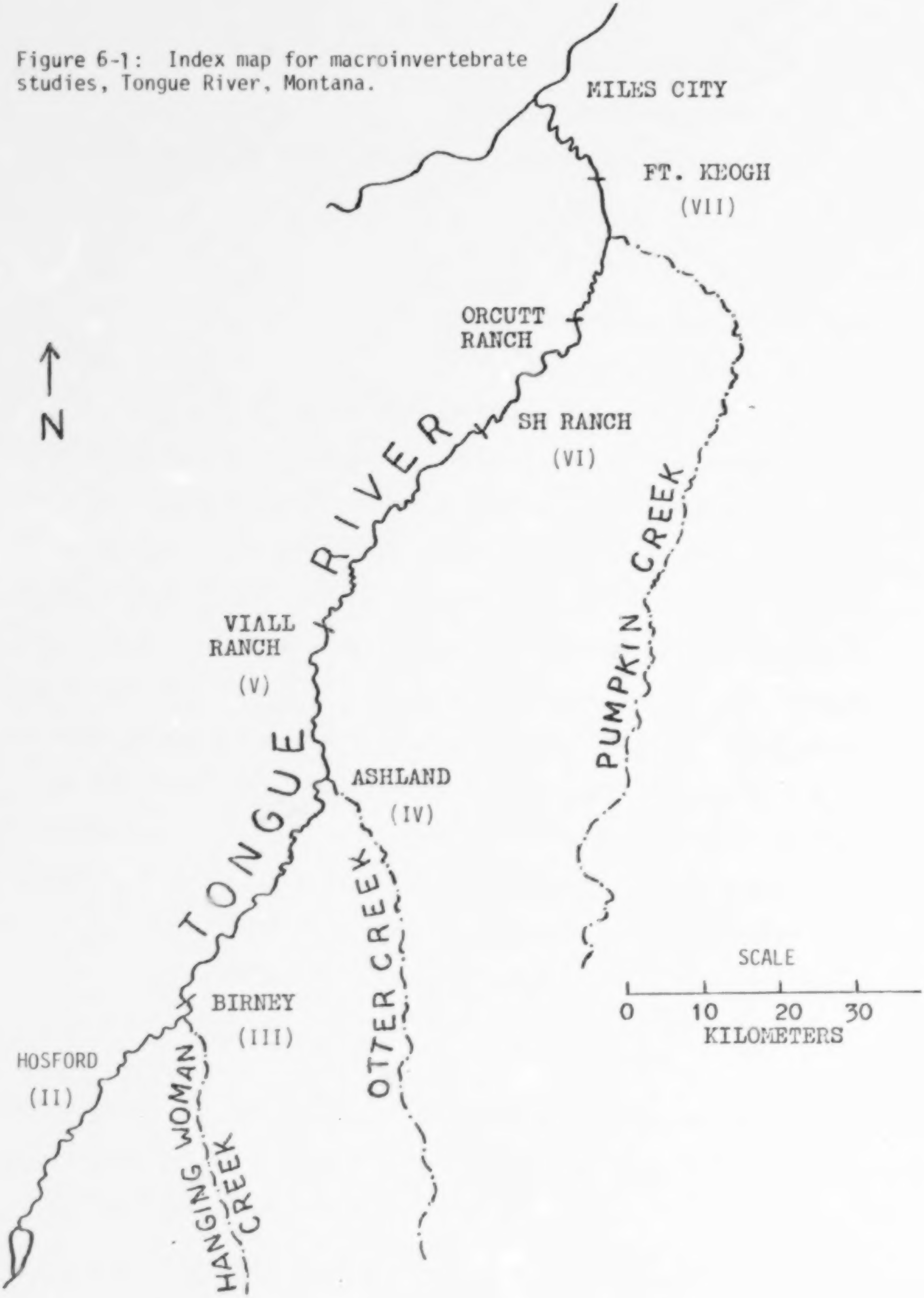
X^2 was also computed for the outlined block in Table 6-1 to determine whether a significant difference exists within the suggested range of depths and velocities. For the outlined area, X^2 was 5.1010, with 2 d.f. The null hypothesis should be rejected, indicating that there is a significant difference in distribution, even within the area selected as flow criteria. However, X^2 computed for depth classes 31-60 cm., and velocity classes 46-75 cm./sec., was nearly zero. Thus, the null hypothesis was not rejected at the 90% level (p = .10) for this depth-velocity class. The velocity class 76-90 cm./sec. introduces a statistically significant variation, but the variance is positive, suggesting that this velocity range should remain part of the velocity criteria.

Streamflow Criteria Based on Benthic Macroinvertebrate Studies:

During a one-week period in March, July, and September, 1975, a total of 225 Hess samples were taken at riffles located at Birney, Montana (Station III), the Viall Ranch near Ashland, Montana (Station IV), and the Hosford Ranch just downstream of the Tongue River Reservoir (Station II, Fig. 6-1). These particular sampling times were chosen, based on distributional information presented in Appendix D, so that the summer, winter, and a transitional fauna between summer and winter were sampled and analyzed. Samples were taken along transects across the river at one meter intervals and up to the limit of the sampling gear (45 cm. depth). For each sample three variables were recorded: depth of the sample, as measured by a wading rod; the current velocity, measured by a Price AA current meter at six-tenths of the depth of the sample (for mean current velocity of that sample); and the microprofile of the substrate itself.

Rather than measure the exact composition of the substrate of each of the 225 samples, the device described in Appendix D allows the investigator

Figure 6-1: Index map for macroinvertebrate studies, Tongue River, Montana.



to rapidly assess the profile of the substrate and obtain some indication of the roughness of the microhabitat.

Velocity, depth, micro-profile, and turbulence (by Froude number, F), where

$$F = \frac{V}{\sqrt{gD}} \qquad \text{(Eq. 6-1)}$$

and: V = current velocity in cm./sec.

D = depth in centimeters

g = acceleration due to gravity (980 cm./sec.^{2})

were evaluated with emphasis on diversity and biomass of insects in the sample, in order to determine optimum flow related conditions.

Based on the assumption that diversity and the biomass of a given species is greatest at the optimum conditions, and will exhibit a clumped distribution around this optimum point, the optimum flow conditions were examined from two perspectives. First, since discharge is related primarily to depth and current velocity, a three-dimensional graph was constructed with diversity, depth, and velocity on the axes. A three-dimensional surface was then constructed. The centroid on this surface was determined to be that depth and velocity where average diversity was at its highest.

Centroids were calculated in the manner illustrated below;

$$C_v = \frac{\sum vH}{H} \qquad \text{(Eq. 6-2)}$$

$$C_d = \frac{\sum dH}{H} \qquad \text{(Eq. 6-3)}$$

where C_v is the centroid for diversity and current velocity and C_d is the centroid for diversity and depth. H, the diversity, is calculated as:

$$H = -\sum_{i}^{s} p_i \ln p_i \qquad \text{(Emlen, 1973)} \quad \text{(Eq. 6-4)}$$

where p_i is the proportion of the i-th species of s species within the sample and ln p_i is the naperian logarithm of p_i. An indicator species, showing adequate streamflow conditions, should have a range of tolerances similar to conditions of maximum diversity, as well as a centroid location close to the centroid for optimum conditions of diversity (COCD). For individuals of a given species in a sample, N replaces H in equations (6-2) and (6-3), where N is the number of individuals of each species. Centroids determined from the graphs of individual species distribution as a function of velocity and depth were compared with the centroid for optimum conditions of diversity (COCD). Those species which showed the most restricted pattern of tolerances to depth and current velocity, and whose centroid most closely matched that of the COCD, were then considered to be potential indicator species. The presence of the indicator species in future sample collections would indicate maintenance of community structure as it was found during this study.

The thickness of the laminar boundary layer along the substrate often determines the microdistribution of invertebrates within a riffle (Hynes, 1970). Turbulence, which is related to depth and velocity, and the profile of the substrate, determine the depth of this boundary layer. To determine the preferences of invertebrates for substrate and turbulence, similar three-dimensional surfaces and centroid calculations were made. Froude number, micro-profile index, and diversity or number of individuals in a species were used as the variables. The centroid calculations are:

$$C_f = \frac{\sum fH}{\sum H} \qquad \text{(Eq. 6-5)}$$

$$C_i = \frac{\sum iH}{\sum H} \qquad \text{(Eq. 6-6)}$$

where C_f is the centroid for turbulence and diversity and C_i is the centroid for micro-profile and diversity. The values v, d, f, and i refer to current velocity, depth, Froude number and micro-profile index for the i-th sample being examined. Centroids for the individual species were calculated by substituting N for H in equations (6-5) and (6-6). The centroid for diversity was assumed to show the substrate and turbulence at which community structure was at its optimum. Potential indicator species were again determined and compared with the indicators from the depth and velocity analyses to determine if a single indicator species could be chosen.

The relationship between diversity, current velocity, and depth is shown in Table 6-2 in which average diversity is presented over increments of 10 cm. of depth and 15 cm. /sec. of current velocity. At this rather large scale, a clumped distribution of high diversities is apparent. The highest average diversities occur in an area where depth is from 20 to 40 cm. and current velocities from 75 to 120 cm. /sec. By using each sample point, rather than these large increments, the centroid on a better defined surface has been determined. The centroid, that is, the point of maximum average diversity, falls within this range at a point represented by a current velocity of 76 cm./sec. and a depth of 28 cm.

Table 6-3 shows diversity compared with turbulence (F) and bottom profile (I). A defined range on this incremental graph is not obvious and one can conclude that turbulence and bottom profile do not influence microdistribution as much as current velocity and depth. Using individual sample values to compute the COCD for turbulence and profile, an F of approximately 0.401 and an I of 2.02 were calculated to represent the optimum conditions. These values correspond to a streaming flow of moderate turbulence and a bottom profile represented by a combination of smooth and angular cobble, and are supported by findings of Wene and Wickliffe (1940), Cummins (1964), Torup (1964) and Egglishaw (1969), all of whom conclude that rubble areas of riffles are the most productive areas for aquatic insects.

A flow of 76 cm. /sec. and a depth of 28 cm. provides an F value of 0.459. Thus, optimum turbulence conditions will be maintained by the rec-

Table 6-2: Relationship between diversity of aquatic invertebrates and current velocity and depth.

	Depth in cm.				
Velocity in cm./sec.	0 - 10	10 - 20	20 - 30	30 - 40	40 - 50
0 - 15	0.667	1.112	1.405	1.530	1.371
16 - 30	1.348	1.218	1.957	1.054	1.505
31 - 45	1.628	1.893	1.977	1.933	1.845
46 - 60	1.440	1.721	1.605	1.958	1.812
61 - 75	1.523	1.703	1.728	2.034	1.612
76 - 90	1.652	1.809	2.319	2.190	2.156
91 - 105	1.203	1.983	2.211	1.844	2.072
105 - 120	1.386	1.661	2.612	2.027	1.724
>120	0.541	1.802	2.131	2.301	1.817

Table 6-3: Relationship between diversity of aquatic invertebrates, and turbulence and bottom configuration.

Froude Number	Microprofile Index 0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	2.0 - 2.5	2.5 - 3.0	3.0 - 4.0
0 - .1		1.399	1.327	1.744		
.1 - .2	1.609		1.356	1.400	1.995	
.2 - .3		2.119	2.099	2.000	1.657	
.3 - .4	1.310	1.871	1.689	1.978	2.064	
.4 - .5	1.946	2.080	1.745	2.017	1.959	2.366
.5 - .6		2.763	2.040	1.560	1.072	
.6 - .7			2.111	1.875		2.600
.7	1.476			2.025	1.750	

ommended COCD for current velocity and depth. Therefore, a flow of 76 cm. /sec. and a depth of 28 cm. over the maximum amount of smooth and angular medium cobble in a given riffle will tend to maintain the aquatic community with a minimum of change.

Figures D-2, D-4, and Table D-1 in Appendix D show the graphic representation of the optimum conditions for representative mayflies compared to the COCD and the actual values of these centroids. Of the species examined, Ephoron album, Traverella albertana, and Rhithrogena hageni show centroids which are close to the COCD of current velocity and depth, and have the narrowest range of tolerances. Ranges of tolerances were diagramatically produced and rounded to include at least 80% of the samples containing individuals of that species being examined. Baetis tricaudatus, Ephoron album, and Rhithrogena hageni show these same kinds of requirements for profile and turbulence. A potential indicator species from the group should show these patterns for all four variables; therefore, Traverella and Baetis are eliminated from consideration as an indicator species.

Overlap of preferred ranges, with the range of maximum diversity, is good in both Ephoron and Rhithrogena. However, Britt (1962) indicates that substrate preferences of Ephoron may be of a greater variety than Tongue River data indicates. In addition, Ephoron is a short-lived summer species and would be a valid indicator for only three months out of a given year. Rhithrogena, on the other hand, occurs in the nymphal stage during the entire year, and as such would be likely to appear in any benthic sample taken which might be used to test for the presence of adequate streamflow conditions. In addition, the adaptation of Rhithrogena to swift waters (the dorso-ventrally flattened body with gills being modified to form a holdfast for free movement on the upper surfaces of rocks in the face of the strongest currents), as shown by Dodds and Hisaw (1924), Percival and Whitehead (1929), Linduska (1942), Nielsen (1950), and Hynes (1970), indicates that Rhithrogena would be the best mayfly indicator not only of good current velocity and depth conditions, but of smooth and angular cobble substrate as well.

Figures D-2 through D-31 in Appendix D show the range of tolerances of current velocity, depth, turbulence, and bottom profile for 38 of the most common invertebrates inhabiting the Tongue River. Table 3 in Appendix D lists the centroid, or approximate optimum condition, for each of the 38 species. Although many of the invertebrate species examined have ranges of tolerances which overlap the conditions of maximum diversity, the total range of tolerances are usually so wide that these species would probably not be sensitive indicators of adequate streamflow.

The Diptera examined suggest another potential indicator species (Figures D-26 and D-27, Appendix D). Simulium sp. has a range of velocity and depth tolerances which overlap well with the area of maximum diversity, as well as a centroid which is close to the COCD. Simulium also extends into the cold water section of the river and would be the primary indicator in this section as Rhithrogena has not been found in this area of the river. In addition, a substrate index of 2.23 indicates the presence of the optimum substrate profile as well. Nielsen (1960) and Hynes (1970) have pointed out the adaptive structures which Simulium employs in its torrential habitat. The requirements of Metriocnemus sp. are similar to Simulium, but the range of tolerances for current velocity and depth do not overlap as well as Simulium with the maximum diversity area.

Rhithrogena hageni and Simulium sp. have been chosen as the best indicator species. The presence of one or both of these indicators in a benthic sample taken in a riffle of medium cobbled substrate would indicate that adequate streamflow parameters to preserve the present invertebrate community are being maintained. It should be noted that Rhithrogena is the primary indicator species. Although the presence of Simulium will indicate maintenance of adequate streamflow parameters, the absence of Rhithrogena from benthic samples taken over several months may mean that streamflow levels should be re-assessed. Simulium, alone, is not as sensitive to altered flow conditions as Rhithrogena.

Flow Criteria for Spawning:

Two potential spawning indicator species, the sauger and the shovelnose sturgeon, were sampled extensively during the spawning runs of 1975 and 1976. The primary objective of the 1975 sampling program was to determine the locations of spawning grounds, and to test various methods of sampling in high, turbid waters. One highly utilized spawning area for both species was located by Montana Fish and Game personnel, and in 1976, the area was staked out and hydrologically mapped as a critical area (See Appendix E).

Sauger Spawning:

Sampling for sauger began on March 23, 1976, when the water temperature reached 7.8°C. A modified boom shocker was rigged to a small drift boat. Power was supplied to the electrodes by a 3000 watt generator which was rectified from AC to DC. Markers, such as those used for the stonecat, were dropped when large concentrations of sauger were encountered. The function of the markers was essentially to outline the areas where large numbers of fish had congregated, rather than to mark individual locations. Several short shocking runs were made within each sampling section, and areas of congregation were measured for depth, velocity, and bottom type.

Concentrations of sauger were typically found in water depths of from 75 to 105 cm., with velocities from 64 to 90 cm./sec. The bottom type was most typically fine to coarse sand, and it was observed that stream areas with dune configuration on the bottom yielded more fish than did areas with planar bottoms. It is surmised that individual sauger were resting in the nodes between the dunes.

Unfortunately, the above flow parameters can not be used as flow criteria. During the entire 2 month sampling program, not a single ripe female was taken from any of the Tongue River sampling sections. The large concentrations of sauger were composed entirely of ripe males. Unless the females moved up from the Yellowstone River each night, and returned early each morning, it must be concluded that spawning of sauger was limited, if not completely excluded, in the Tongue River during 1976.

Haddix (1976) observed large congregations of sauger and walleye in the Yellowstone River during 1976. He noted that both species collected over large gravel bars, and was able to demonstrate that spawning had occured by collecting the eggs of both species. At the time of egg collection, the depth of the spawning sites ranged from 27 to 43 cm., with velocities between 11 and 27 cm./sec. However, insufficient data was collected to perform statistical analyses, or to demonstrate spawning preferences.

Shovelnose Sturgeon Spawning:

The sampling effort for shovelnose sturgeon proved to be more successful than for spawning sauger. Sampling was accomplished by drifting a 7.5 cm. mesh gill net through areas known to contain large concentrations of ripe sturgeon. When sturgeon become entangled in a gill net, they fight to the surface with a great deal of splashing, and then retreat back toward the bottom. Because of this unique behavior, it was possible to determine with fair accuracy, the approximate location of the sturgeon as the net drifted over them. Whenever a new sturgeon fought to the surface, a buoy was thrown to mark the position. At the end of each drift, measurements of depth, velocity, and bottom type were made at 3 to 4 locations around each marker. The data for each marker was then averaged, to give a mean depth and velocity for each sturgeon captured. The measurement and averaging of flow parameters in the general vicinity of capture is probably more valid than a single measurement, because it was not possible to see exactly where each captured sturgeon was located. Most of the sturgeon collections contained both ripe males and females.

Virtually all of the sturgeon captured were found over bottoms of sand, or sand and gravel. Like the sauger, they appeared more plentiful where the streambed was dune-form rather than planar. Water depths ranged from 40 to 110 cm., with velocities between 50 and 110 cm./sec. Table 6-4 shows the frequency of occurrance of captured sturgeon during the 1976 spawning run.

Table 6-4: Frequency of occurrance of ripe shovelnose sturgeon, according to depth and velocity groupings.

DEPTH IN CM

VELOCITY IN CM/SEC	40-50	51-60	61-70	71-80	81-90	91-100	101-110	Total
50-60					2			2
61-70			1	4	4		3	12
71-80	1	1	13	5	4	2	1	27
81-90		1	1	3		5	1	11
91-100			6	5	4	4		19
101-110		1		2	4			7
Total	1	3	21	19	18	11	5	78

The null hypothesis was defined as: there is no significant difference in the distribution of depth classes within velocity classes of sturgeon captured. X^2 was calculated for Table 6-12, giving a value of $X^2 = 33.38667$

with 15 d.f. Therefore, the null hypothesis was rejected at the .995 level.

Tentative flow criteria were established by combining depth and velocity classes until no significant difference in the observed frequencies was detected, for at least the .80 level. Table 6-5 shows the suggested flow criteria as determined by this method.

Table 6-5: Flow criteria for spawning shovelnose sturgeon as determined by the combination of depth and velocity classes.

VELOCITIES IN CM/SEC	DEPTH IN CM 60-80	81-100	Total
70-90	22	11	33
91-110	13	12	25
Total	35	23	58

X^2 for this table was 1.27864 with 1 d.f. The null hypothesis could not be rejected up to the .75 level (.75>p>.50). Table 6-13 contains nearly 75% of all the sturgeon sampled. However, due to the rather small sample size, the above criteria should be considered tentative and subject to revision as more information is collected.

The failure of sampling efforts to detect spawning sauger points out the problems involved in determining spawning flow criteria. It is possible, if not probable, that the sauger did not spawn in the Tongue River during the 1976 run. Obtaining flow criteria is not difficult, but it does require the full co-operation of the fish. It is recommended that further attempts be made to document hydrologic parameters over spawning sites. In view of the unpredictable behavior of some species, it may take three to five years of data collection before sufficient information can be gathered. However, the problem is important enough to commit a major effort and full scale study.

Measurement and Mapping of Hydrologic Parameters

Multiple Transect Analysis (MTA):

Collings, et. al. (1972) first developed the technique of multiple transect analysis (MTA) for the purpose of evaluating the effects of streamflow on discrete salmon spawning areas. While MTA is probably the most reliable field technique presently available for the recommendation of spawning or rearing flow requirements, it is, unfortunately, more easily explained than implemented.

MTA utilizes a series of transects, arranged perpendicular to the flow, along which the measurements of depth, velocity, and bottom type, are made. In the Tongue River, four transects spaced 6 meters apart were established over the critical rearing areas under examination, and up to 10 transects spaced from 12 to 30 meters apart were used to assess passage and spawning flows. Measurements of depth, velocity, and bottom type were made at 1.5 or 3.0 meter intervals on each transect; the distance between measuring points was dependent on channel uniformity. Cross-sectional depth and (mean water-column) velocity for each discharge were then plotted on separate planimetric maps of each study reach. Isolines of equal depths and velocities were then drawn on the maps. Depth and velocity contour maps for rearing and spawning critical areas can be found in Appendix A and Appendix E, respectively.

Flow Prediction Models Used with MTA:

The process of repeatedly measuring the hydrologic parameters across multiple transects is undeniably the most reliable technique for obtaining field data. Unfortunately, this technique has two significant faults which detract from its otherwise attractive features. The first is an imposing time requirement. Each contour map set in Appendix A and E represents approximately 3 man-days of work; however, field and office time is only a small part of total time requirements. If streamflow is stable, several weeks may pass before sufficient change in flow has occurred to warrant remapping a section.

The second difficulty with direct measurement is that of streamflow regimen. Often, flows will be too high to obtain good low-flow maps of the section. Thus, the range of flows mapped may be severely restricted, particularly if the streamflow is regulated.

These problems may be partially or totally circumvented by the use of flow prediction models. While such models should not be construed as complete substitutes for field measurement, they are useful tools to the water resource planner. However, the planner may be hesitant to use a model if the reliability of the output is in question. Therefore, the accuracy of streamflow prediction models must be addressed before planners can use them with confidence. Two flow prediction models were implemented and field tested in the Tongue River to achieve this objective.

Water Surface Profile Program (WSPP):

The Water Surface Profile Program is a computer adaptation of the U.S. Bureau of Reclamation's Water Surface Profile Computation Method B. The WSPP Program was written to computerize the computations necessary to determine water surface elevations at reservoirs and below dams. It is adaptable to in-stream flow applications by predicting changes in stream characteristics at many different flows,without making numerous field observations at these flows.

The WSPP is essentially an energy balance model, generally following the Bernoulli equation for open channel flow. However, the computer program utilizes the Manning equation to predict hydraulic values at various streamflows. The Manning equation is as follows:

$$V = \frac{1.49\, R^{2/3}\, S^{1/2}}{n} \qquad \text{(Eq. 6-7)}$$

Where:

V = Velocity

R = Hydraulic Radius (Area/Wetted Perimeter)

S = Slope of Energy Grade Line

n = Roughness Coefficient

The value "n" in the Manning equation commonly varies across a transect, or between transects. For the WSPP, "n" is calculated for sub-sections of each transect, from known velocities, hydraulic radii, and energy gradients.

Field data requirements for the WSPP are modest, although a survey team of two to three persons is required to obtain the data. Data requirements include:

1. Cross-sectional data at each transect.
2. Distance between transects.
3. Measured discharge and velocity.
4. Water surface elevation at each transect at the measured flow.
5. Description of the streambed materials at each cross-section.
6. Identification of points along a transect where bottom materials change.
7. Description of bank and overbank materials and vegetation.

Complete descriptions of the WSPP may be found in Spence (1975) and Dooley (1975).

A field test of the WSPP was conducted during November, 1975. Measurements for the program were made at the SH Ranch section and the Viall mapping section. Water surface elevations were re-surveyed at the SH section to determine the accuracy of the model for predicting elevations, which then can be used to determine depths. Table 6-6 shows the predicted water surface elevations compared to those measured at 2.38 cms. flow in the SH section.

Table 6-6: Predicted and Measured Water Surface Elevations (meters) at SH section, Tongue River, at 2.38 cms.

Program	302.86	302.98	302.99	303.02	303.04	303.07	303.09
Actual	302.89	302.98	302.99	303.04	303.04	303.05	303.06
Absolute Deviation	0.03	0.01	0.01	0.02	0.00	0.02	0.03

No significant difference p>.20

Ref: Elser, A.A., 1976. "Use and Reliability of the Water Surface Profile Program Data on a Montana Prairie Stream," In-Stream Flow Needs Symposium, AFS-ASCE, Boise, May 3-6, 1976.

Data in Table 6-6 was subjected to a paired data, two-tailed significance test. No significant difference between predicted and measured values was detected at the 80% level (p>.20), and the predicted elevations are considered to be reliable (Elser, 1976).

The accuracy of WSPP in the prediction of velocities was tested at transect C of the Viall mapping section. Measured velocities were compared with predicted velocities for five different discharges. The results of this field test are summarized in Table 6-7.

Table 6-7: Comparison of predicted and measured velocities in cm./sec. at Transect C, Viall Section at various flows.

		Sub-section				
		1	2	3	4	5
Flow = 2.83 cms.						
	Program	58	66	47	26	45
	Actual	47	44	43	40	27
	Deviation	11	22	4	14	18
	$t = 1.333$	No Significant Difference at $p>.20$				
Flow = 4.25 cms.						
	Program	61	72	56	34	51
	Actual	55	51	56	28	40
	Deviation	6	21	0	6	11
	$t = -2.49$	Significant Difference $p<.10$				
Flow = 5.66						
	Program	63	76	61	42	54
	Actual	61	58	58	45	50
	Deviation	2	18	3	3	4
	$t = -1.353$	No Significant Difference, $p>.20$				
Flow = 7.36 cms.						
	Program	67	79	65	48	59
	Actual	57	64	75	64	61
	Deviation	10	15	10	16	2
	$t = 0.1055$	No Significant Difference, $p>.90$				
Flow = 11.04 cms.						
	Program	76	86	75	61	70
	Actual	78	75	81	68	79
	Deviation	2	11	6	7	9
	$t = 0.1749$	No Significant Difference, $p>.80$				

Ref: Elser, A.A. 1976. op. cit.

A paired-data, two-tailed significance test was performed for the predicted and measured values of velocity. No significant difference was found at the 80 percent level (p>.20) at flows of 2.83, 5.66, 7.37, and 11.04 cms. A significant difference was detected for the 4.25 cms. flow. However, examination of the data shows only one sub-section with a sizeable error. It should be stressed that an error of ± 10 cm./sec. is not unreasonable in highly turbulent, non-uniform flow such as that found in Viall Transect C.

CONTOUR Program:

The CONTOUR Program was developed during the Tongue River study to overcome a serious problem in the utilization of the WSPP in multiple transect analysis. The WSPP is capable of predicting only average velocities across relatively large sections of transects. Such averages cannot be used in drawing planimetric maps such an those in Appendix A. A model which could reasonably predict the velocity at a single point in the river is required for planimetric mapping, and CONTOUR was designed for this purpose.

CONTOUR is based on a fairly elementary concept in stream hydrology. Because a channel must transmit varying amounts of water during the year, the observed mean velocity, mean depth, and width, at different discharges, reflect the hydraulic characteristics of the cross-section. Plotting these three functions against discharge, on log-log paper, tend to show a straight line relation. With increasing discharge at a given cross-section, the width, mean depth, and mean velocity each increase as power functions (Leopold and Maddock, 1953), shown as follows:

$$w = aQ^{b} \; ; \; d = cQ^{f} \; ; \; v = kQ^{m} \qquad \text{(Eq. 6-8. 9, 10)}$$

The CONTOUR program assumes that these relationships hold for individual, as well as mean, depths and velocities. Data and manpower requirements for CONTOUR compare favorably with the WSPP. In fact, data for both may be taken concurrently if so desired. A study area, such as a critical area as discussed earlier, is mapped in exactly the same manner as direct measured MTA, at two widely different discharges. The only difficult requirement for data collection is that all measurements must be made at exactly the same locations for both discharges. These locations should be identified in the field notes as data is collected (i.e. Transect C, point 10).

Each point in the stream is then subjected to a logarithmic regression using the depths and velocities measured at each point at the two discharges. A computer program has been written to 1) calculate the constants "C" and "k", and the exponents "f" and "m" for the depth-velocity power functions at each location; 2) calculate predicted depths and velocities at various streamflows; and 3) display the output in an easily readable matrix. These calculations may also be made with an electronic calculator, but the computations are quite tedious. This "simulated" data may then be used in the construction of contour maps such as those in Appendix A and D.

The CONTOUR program was field tested on the same transect as was the WSPP program to determine its comparability, and thereby its accuracy. Tables 6-8 to 6-11 show the predicted and measured velocities at 18 points along the transect at flows of 4.02, 5.58, 6.37, and 10.20 cms., respectively. Predicted values for velocity compared to the measured values showing no significant difference at the 10% level (p>.90) for flows of 4.02 and 5.58 cms.

Table 6-8: Comparison of predicted and measured velocities in cm./sec., using the CONTOUR Program, at Transect C, Viall Section.

Flow = 4.02 cms.

Point	Measured	Predicted	Difference
C2	11	17	-6
C3	80	78	2
C4	53	58	-5
C5	71	72	-1
C6	60	59	-1
C7	50	50	0
C8	41	55	-14
C9	40	30	10
C10	52	63	-11
C11	64	56	8
C12	61	55	6
C13	52	45	7
C14	71	65	6
C15	49	41	8
C16	49	55	-6
C18	32	43	-11
C26	40	36	4
C27	0	0	0

t = -0.0645 No Significant Difference, p>.90

Table 6-9: Comparison of predicted and measured velocities in cm./sec., using the CONTOUR Program, at Transect C, Viall Section.

Flow = 5.58 cms.

Point	Measured	Predicted	Difference
C2	21	26	-5
C3	76	86	-10
C4	60	65	-5
C5	78	80	-2
C6	71	71	0
C7	46	54	-8
C8	47	60	-13
C9	63	40	23
C10	59	69	-10
C11	61	62	-1
C12	73	62	11
C13	52	53	-1
C14	78	67	11
C15	40	50	-10
C16	53	60	-7
C18	67	52	15
C26	60	46	14
C27	0	0	0

t = 0.0454 No Significant Difference, $p > .90$

Table 6-10: Comparison of predicted and measured velocities in cm./sec., using the CONTOUR Program, at Transect C, Viall Section.

Flow = 6.37 cms.

Point	Measured	Predicted	Difference
C1	0	8	-8
C2	12	30	-18
C3	78	90	-12
C4	67	63	4
C6	76	76	0
C7	55	56	-1
C8	63	63	0
C10	66	71	-5
C12	71	65	6
C14	80	68	12
C15	80	55	25
C16	66	63	3
C19	80	81	-1
C20	56	50	6
C24	67	32	35
C26	67	51	16
C27	0	0	0

t = 1.1619 No Significant Difference, p>.20

Table 6-11: Comparison of predicted and measured velocities in cm./sec., using the CONTOUR Program, at Transect C, Viall Section.

Flow = 10.20

Point	Measured	Predicted	Difference
C1	10	22	-12
C2	56	52	4
C4	80	79	1
C6	98	98	0
C7	61	63	-2
C8	70	71	-1
C10	89	80	9
C12	80	76	4
C13	67	70	-3
C15	98	73	25
C16	87	71	16
C18	73	76	-3
C19	67	98	31
C21	71	66	5
C23	66	50	16
C25	70	59	11
C26	87	74	13
C27	0	0	0

t = 1.0019 No Significant Difference, p>.30

There was no significant difference at the 70 percent level ($p > .30$) at 10.20 cms., and no significant difference at the 80% level ($p > .20$) at 6.37 cms. Therefore, it is suggested that the CONTOUR Program is at least as reliable as the WSPP for predicting velocities. In addition, CONTOUR also predicts point velocities in the stream.

CONTOUR may also be used to predict depths at specific locations across a transect. Tables 6-12 to 6-15 compare the predicted and measured values for depths on Viall Transect C. Although the predicted values are usually within 1 or 2 cm. of the actual depths, the paired data (t) test reveals a significant difference at 4.02 and 5.58 cms. This difference results from the predicted depths for those flows being consistently higher than the measured depths. There was no significant difference at 10.20 cms. ($t = 1.2249$, 17 d.f., $p > .20$) or at 6.37 cms. ($t = 0.6538$, 14 d.f., $p > .50$). Therefore, it is suggested that although CONTOUR can predict depths at specific points on a transect, the WSPP appears to be more reliable in depth prediction. This greater reliability is probably a result of greater accuracy in the measurement of depths. In fast water depths are difficult to measure, and may be in error by as much as 3.0 cm.

Application Of The Methodology

Rearing Flow Recommendation Based on Stonecat Criteria:

Composite maps, outlining the areas meeting both depth and velocity criteria, were drawn from the depth and velocity contour maps in Appendix A. Appendix B contains the composite maps for the Viall and Orcutt sections. Areas not meeting depth-velocity criteria are indicated by cross-hatching on the maps.

The optimum flow is determined by plotting the area meeting flow criteria against discharge. As streamflow increases, the amount of preferred area

Table 6-12: Comparison of predicted and measured depths, using the CONTOUR Program, at Transect C, Viall Section.

Flow = 4.02

Point	Measured (cm.)	Predicted (cm.)	Difference (cm.)
C2	11	12	-1
C3	24	26	-2
C4	31	35	-4
C5	40	39	1
C6	40	43	-3
C7	31	32	-1
C8	31	33	-2
C9	34	36	-2
C10	27	30	-3
C11	31	32	-1
C12	27	30	-3
C13	24	23	1
C14	27	31	-4
C15	24	26	-2
C16	18	23	-5
C18	12	14	-2
C26	27	29	-2
C27	15	15	0

t = -5.0736 Significant Difference, p<.001

Table 6-13: Comparison of predicted and measured depths, using the CONTOUR Program, at Transect C, Viall Section.

Flow = 5.57

Point	Measured (cm.)	Predicted (cm.)	Difference (cm.)
C2	15	16	-1
C3	31	30	1
C4	37	37	0
C5	41	43	-2
C6	43	48	-5
C7	37	35	2
C8	37	39	-2
C9	38	40	-2
C10	31	36	-5
C11	37	37	0
C12	31	36	-5
C13	27	27	0
C14	34	34	0
C15	31	29	2
C16	21	28	-7
C18	18	16	2
C26	31	33	-2
C27	18	19	-1

t = -2.2153 Significant Difference, $p < .05$

Table 6-14: Comparison of predicted and measured depths, using the CONTOUR Program, at Transect C, Viall Section.

Flow = 6.37 cms.

Point	Measured (cm.)	Predicted (cm.)	Difference (cm.)
C1	0	4	-4
C2	18	18	0
C3	37	32	5
C4	40	41	-1
C6	49	50	-1
C7	40	37	3
C8	37	41	-4
C10	37	38	-1
C12	37	38	-1
C14	37	36	1
C15	27	31	-4
C16	24	30	-6
C18	21	17	4
C26	37	35	2
C27	21	22	-1

t = -0.6538 No Significant Difference, p>.50

Table 6-15: Comparison of predicted and measured depths, using the CONTOUR Program, at Transect C, Viall Section.

Flow = 10.20

Point	Measured (cm.)	Predicted (cm.)	Difference (cm.)
C	9	9	0
C2	27	27	0
C4	49	49	0
C6	55	58	-3
C7	43	44	-1
C8	49	51	-2
C10	49	48	1
C12	49	48	1
C13	43	37	6
C15	40	37	3
C16	31	39	-8
C17	24	19	5
C19	31	27	4
C21	27	26	1
C23	18	13	5
C25	27	19	8
C26	46	43	3
C27	27	30	-3

t = 1.2249 No Significant Difference, p>.20

also increases, rising to a well-defined peak. Increased discharges beyond the peak usually exceed the flow criteria, and the size of the preferred area decreases. Trend-fitted curves of preferred area vs. discharge were prepared for the Viall and Orcutt rearing areas, and are shown in Figures 6-2 and 6-3, respectively. The optimum flow at the Viall section was found to be 12.0 cms. (425 cfs.), a flow which provided 425 m^2 of preferred area (57% of the total wetted surface). For the Orcutt section, the optimum flow was 11.1 cms. (392 cfs.), which provides 499 m^2 of preferred area (57% of total wetted surface). According to the methodology proposed by Collings, et. al. (1972), the minimum recommended streamflow is defined as 75% of the optimum flow. Thus, the recommended minimum rearing flow, as determined by stonecat criteria would be 9 cms. (318 cfs.) at the Viall section and 8.3 cms. (294 cfs.) at the Orcutt section.

Rearing Flow with *Rhithrogena hageni* as the Indicator:

Composite maps outlining the area meeting flow criteria for *Rhithrogena hageni* as determined by Gore (1976) are given in Appendix C. Areas not meeting depth and velocity criteria are indicated by cross-hatching on the maps.

Figure 6-4 is a "peak of the curve" plot of optimum insect production area vs. discharge for the Viall mapping section. The optimum flow at the Viall section (Figure 6-4) corresponds to that of Figure 6-2, where the stonecat was used as the indicator species.

Spawning Flow with the Shovelnose Sturgeon as the Indicator:

Hydrologic contour maps of the critical area in the Ft. Keogh section are given in Appendix E. Composite maps were drawn outlining areas meeting criteria for substrate, depth, and velocity. These are included in Appendix F. It is interesting to note that even at very low flows, a part

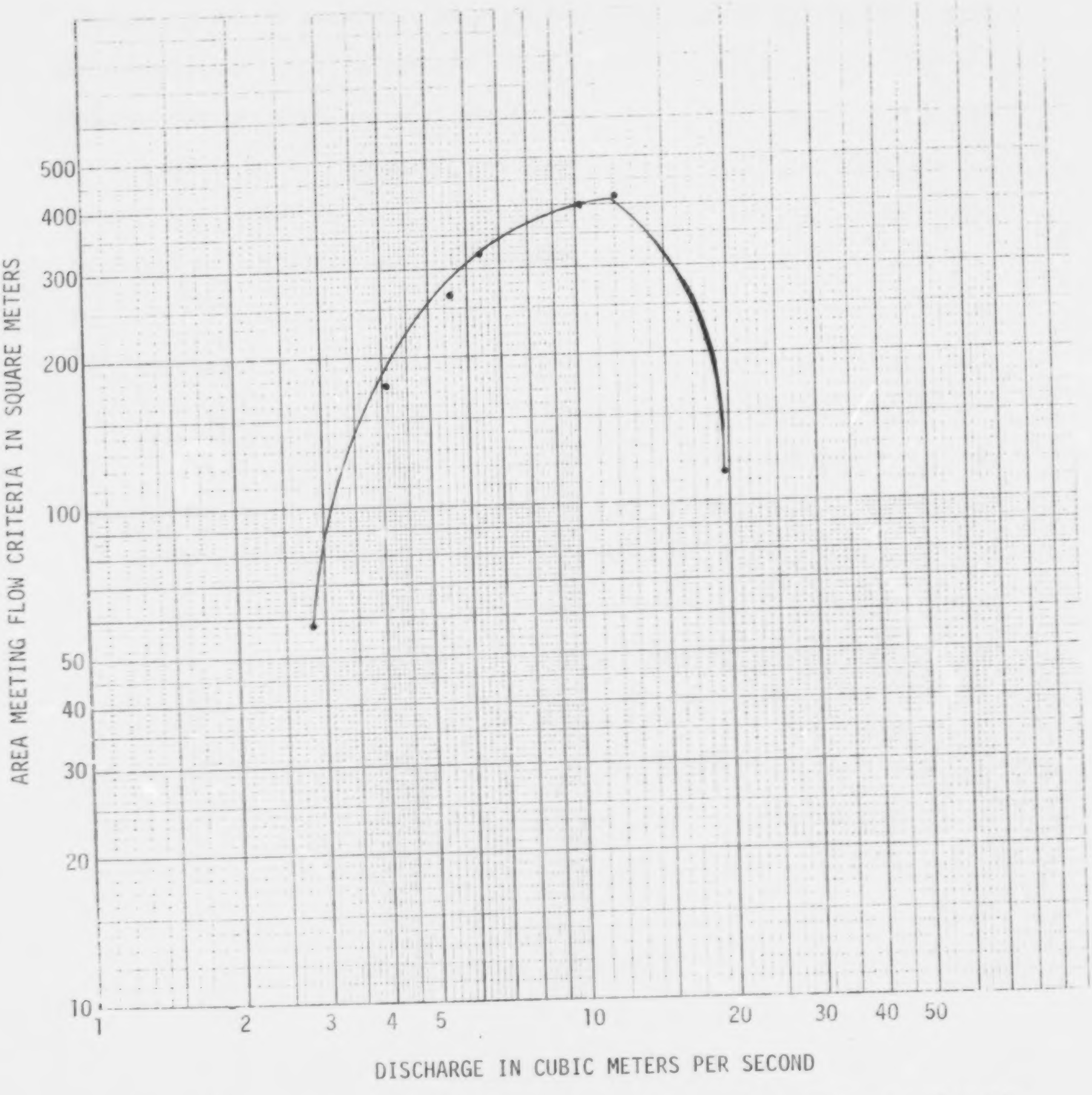


Figure 6-2 "Peak of the Curve" Graph for determining optimum rearing flow, based on flow criteria for the stonecat, Viall Mapping Section. Sustaining rearing discharge is defined as 75% of the optimum flow.

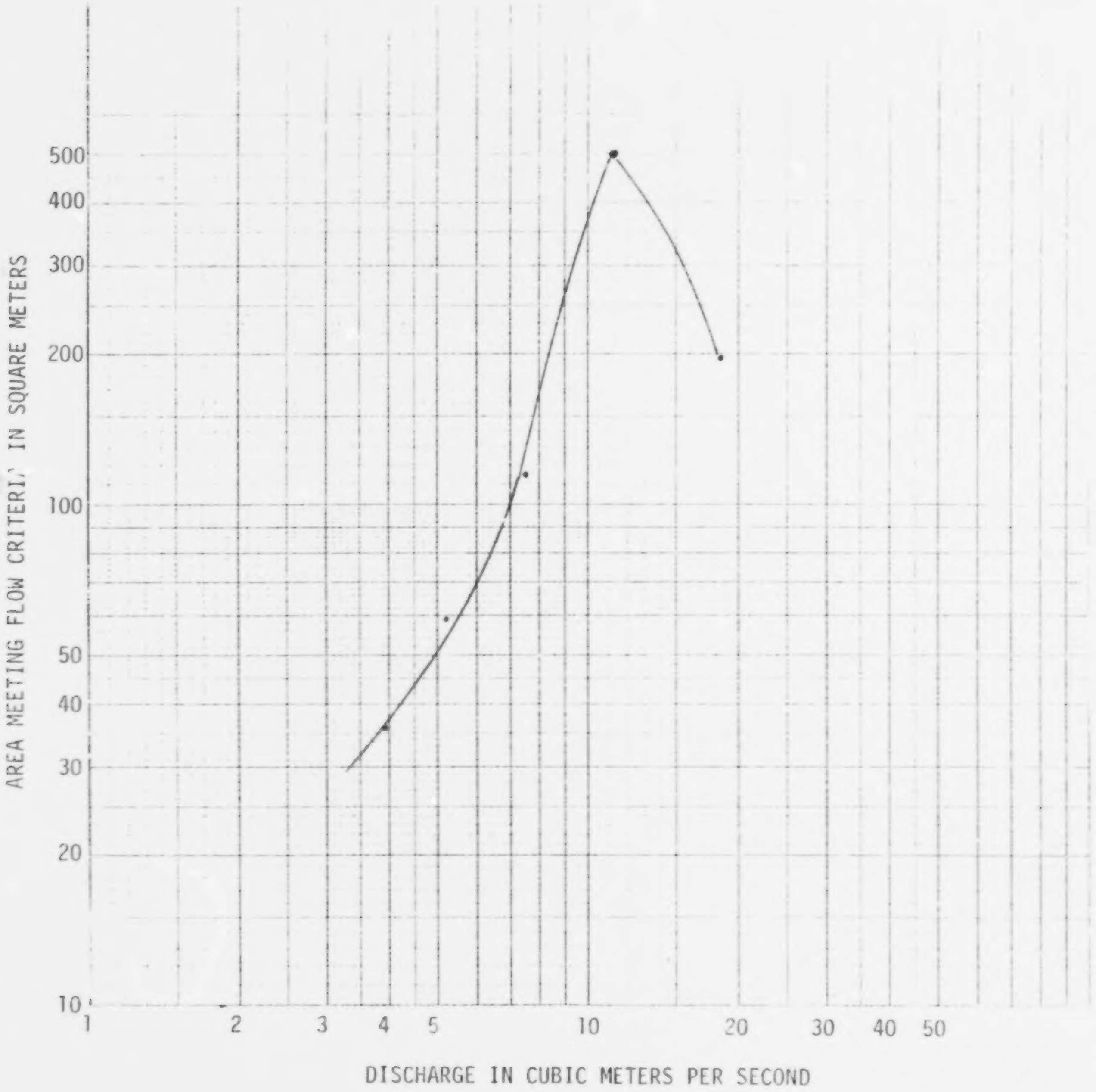


Figure 6-3: "Peak of the Curve" Graph for determining optimum rearing flow, based on flow criteria for the stonecat, Orcutt Mapping Section. Sustaining rearing discharge is defined as 75% of the optimum flow.

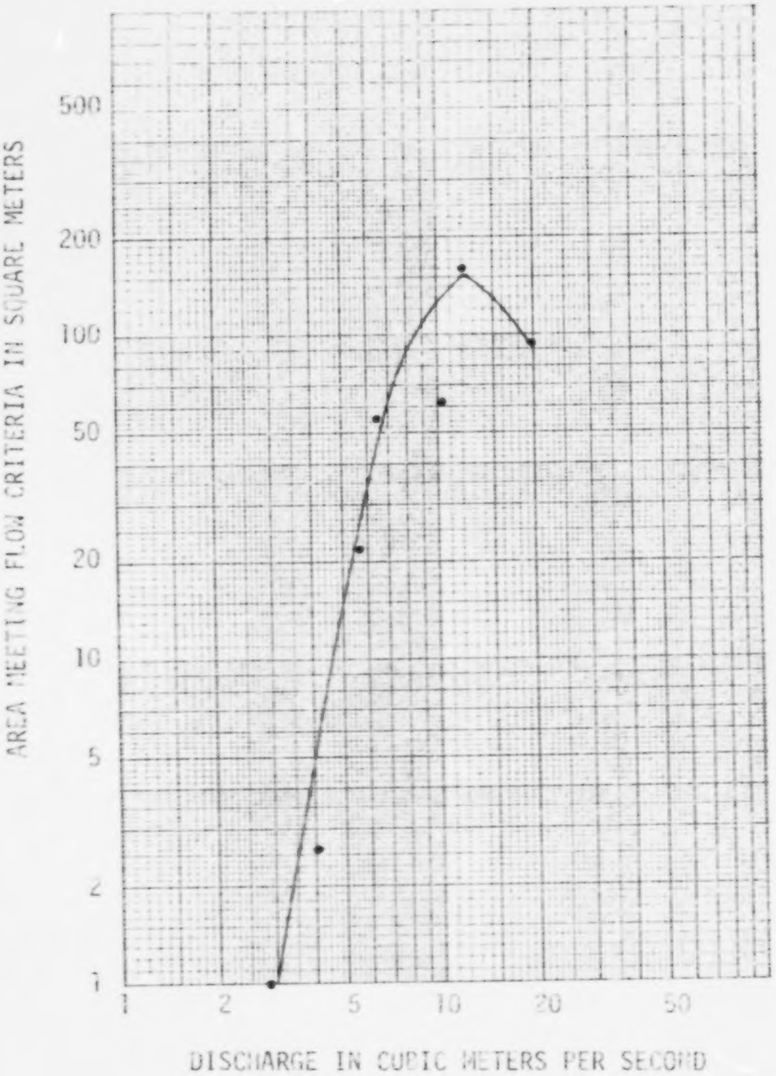


Figure 6-4: "Peak of the Curve" Graph for determing optimum rearing flow, based on flow criteria for Rhithrogena hageni, Viall Mapping Section.

of the mapped section meets the flow criteria. This area is a scour pool which, at low flow, acts like a channel constriction due to its proximity to a large mid-channel sand bar. The scour pool is not considered part of the critical area because it is relatively insensitive to changes in discharge, and is isolated and not contiguous to the remainder of the spawnable area of the channel.

The "peak of the curve" plot for the Ft. Keogh spawning section is shown in Figure 6-5. The inflection point, at about 13.0 cms., is a result of the scour pool, and represents the flow at which new spawning area is being added at the highest rate per incremental increase in discharge. The optimum spawning flow was not reached or mapped in this critical area. By following the trend-fitted curve upward, it is estimated that the optimum would probably occur between 50 to 60 cms., or at near bankful stage.

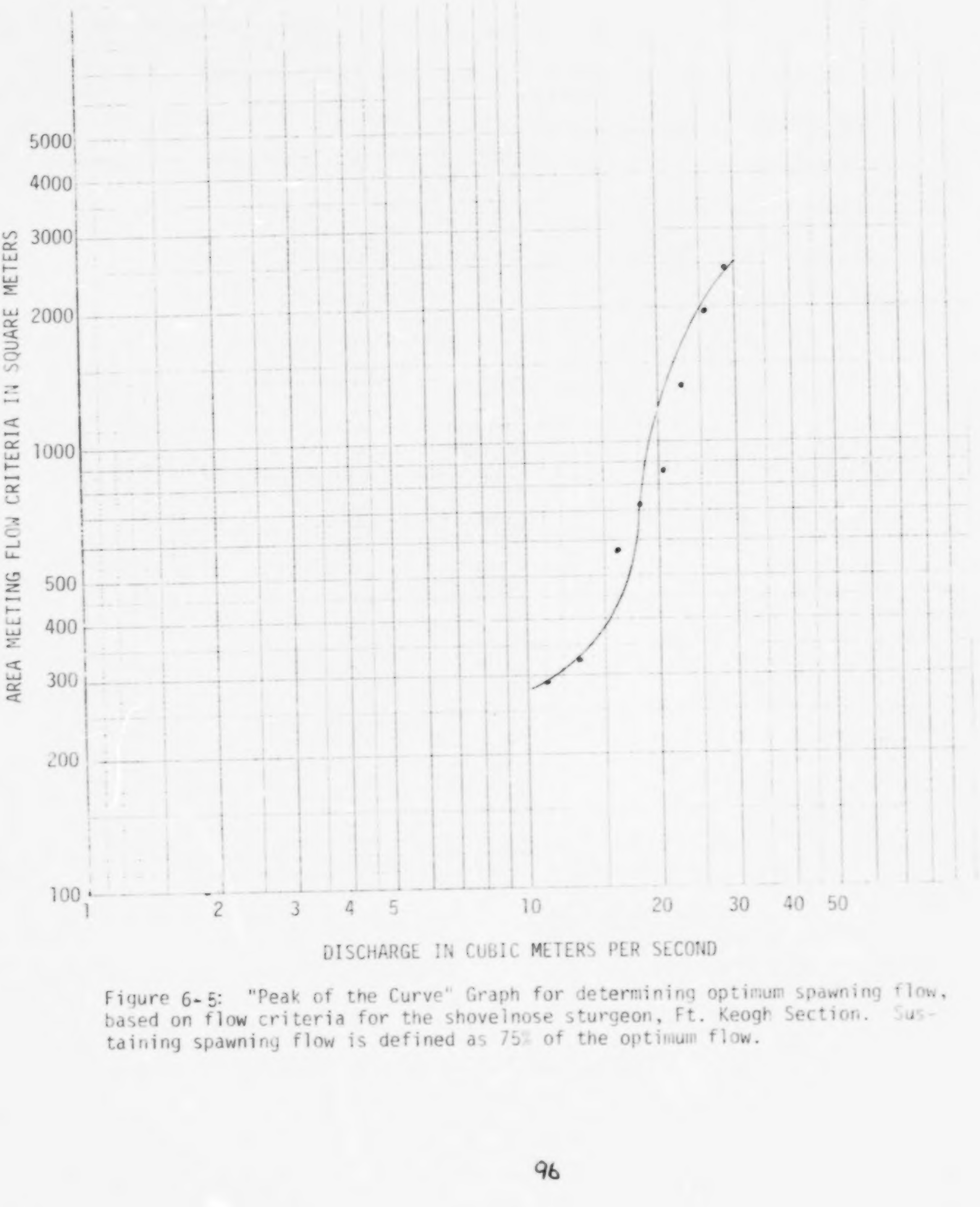


Figure 6-5: "Peak of the Curve" Graph for determining optimum spawning flow, based on flow criteria for the shovelnose sturgeon, Ft. Keogh Section. Sustaining spawning flow is defined as 75% of the optimum flow.

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CHAPTER 7: VALIDATION OF THE FISHERIES COMPONENT METHODOLOGY

Introduction

The objective of using any flow recommendation methodology is the protection of the in-stream resource to which the methodology is applied. Not only must the methodology meet the criteria for scientific reliability, but it must also be legally defensible. When a water resource planner enters an adjudication proceeding to reserve a fishery flow, he must be able to demonstrate 1) the amount of water required to sustain the fishery, and 2) the consequences of reserving an insufficient flow.

A study conducted by Milhous (1973) showed that each of the methodologies used in Montana, Washington, and Oregon tended to over-allocate water for the fishery. That is, more water was "required" to sustain the fishery than was naturally available in the rivers studied. Yet, each river supported a fishery. These findings would be particularly damaging to a planner's flow recommendations in an adjudication proceeding. Therefore, the reliability of a given methodology must be determined, and modifications made to the methodology to insure its validity. To achieve this end, the Indicator Species-Critical Area concept was field tested in the Tongue River.

During the period August to November, 1975, the flow of the Tongue River was altered considerably due to repair procedures at the Tongue River Dam. During August and September, 1975, the level of the reservoir was lowered, resulting in very high discharges to the river. During late September and October, 1975, flows were steadily decreased, and in late October the dam was closed. Groundwater inflow and water pumped over the spillway kept the river from drying up; the lowest streamflow measured at the Viall Ranch, near Ashland, MT., was 2.83 cms. The closure of the

Tongue River Dam enabled researchers to map critical areas at very low flows and to monitor the effects of reduced flow on the aquatic insect community. However, this principal field test was made difficult, and was probably affected somewhat, by wide fluctuations even at reduced flows.

Reaction Of Fish To Flow Reduction

An experimental channel was established at the Viall Ranch, SW 1/4 NW 1/4 Sec 2, T1S, R 44E. Streamflow was diverted to one side or the other around an island, to deplete or augment the flow in the experimental channel. The diversion structure was constructed from cinder blocks and sandbags (Plate 7-1). Because streamflow was initially high when the diversion was built, and then fell steadily during the entire experiment, it was very difficult to keep a constant flow through the experimental channel. However, a continuous vigil was maintained at the diversion site and water level fluctuations in the experimental channel were minimized.

Two riffle areas within the experimental channel were hydrologically mapped using Multiple Transect Analysis (Chapter 6). In addition, the average velocity and maximum depth was determined for two backwater areas and four pools within the channel at several different discharges. Hydrologic maps of the experimental channel are included in Appendix G. Flow criteria for the stonecat were applied to the hydrologic maps, and composite maps showing areas meeting criteria were constructed. The composite maps for the two riffle areas are shown in Appendix H.

Several experimental "runs" were conducted in the channel. At each of several flows, riffle areas and associated habitat areas were mapped and measured. The mapped flow was then maintained in the channel for a two-week acclimation period. At the end of the acclimation period, a

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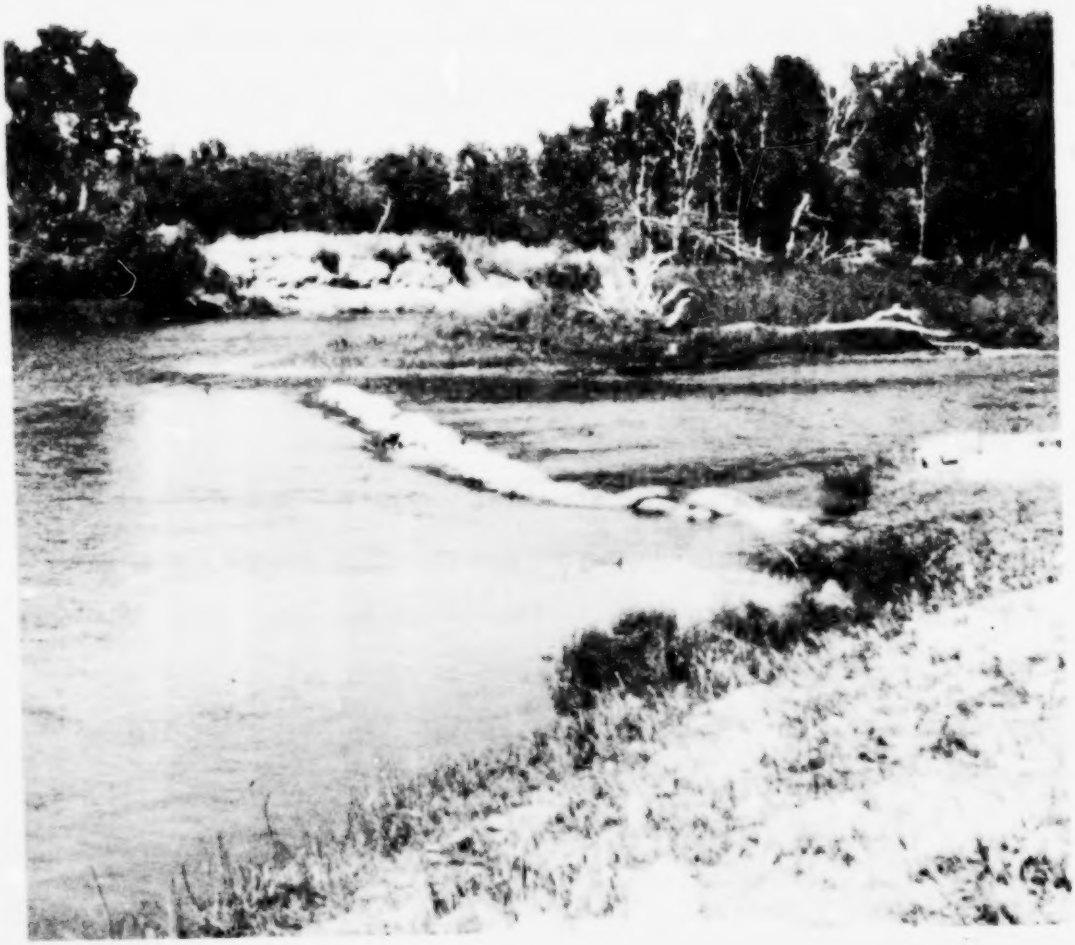

Plate 7-1: Diversion structure, island, and experimental channel at Viall Ranch section. Experimental channel is immediately downstream from the diversion structure.

fish collection was made to determine distribution, species composition, and diversity associated with each flow. A 1500 watt DC electrofishing unit (mobile positive electrode), mounted in a drift boat, was used to make the collections. A 1/2" mesh block net was erected at the lower end of the experimental channel to prevent fish from escaping downstream.

Sampling was done slowly and methodically, ensuring that all microhabitat areas within the channel received equal sampling effort. Each fish captured was examined and keyed immediately. A color-coded buoy was dropped at each capture location to indicate the species captured. The position of each buoy was then plotted on a planimetric map of the channel to indicate the species distribution at each flow.

Results of Hydrologic Mapping:

The optimum streamflow for the experimental channel was determined by the "peak of the curve" method for Riffle #1 and #2, illustrated by Figures 7-1 and 7-2. It can be seen that Figure 7-1 does not peak and decline as expected. This phenomenon was caused by a gravel bar, which extends out from the island into Riffle #1. At very high flows the shelf was flooded and the hydrologic parameters of depth and velocity met the flow criteria for the stonecat. Since gravel is a poor substrate for stonecats, the gravel bar was omitted from the "critical area." Figure 7-3 shows the "peak of the curve" plot for Riffle #1, with the gravel bar area omitted.

The optimum flow for Riffle #1 from Figure 7-3 is 2.01 cms., while the optimum at Riffle #2 occurred at 1.33 cms.

Results of Fish Collections:

If the theoretical optimum flow as determined by the application of the methodology can be equated to a biological counterpart, then there should be some trend in species composition, distribution, or community

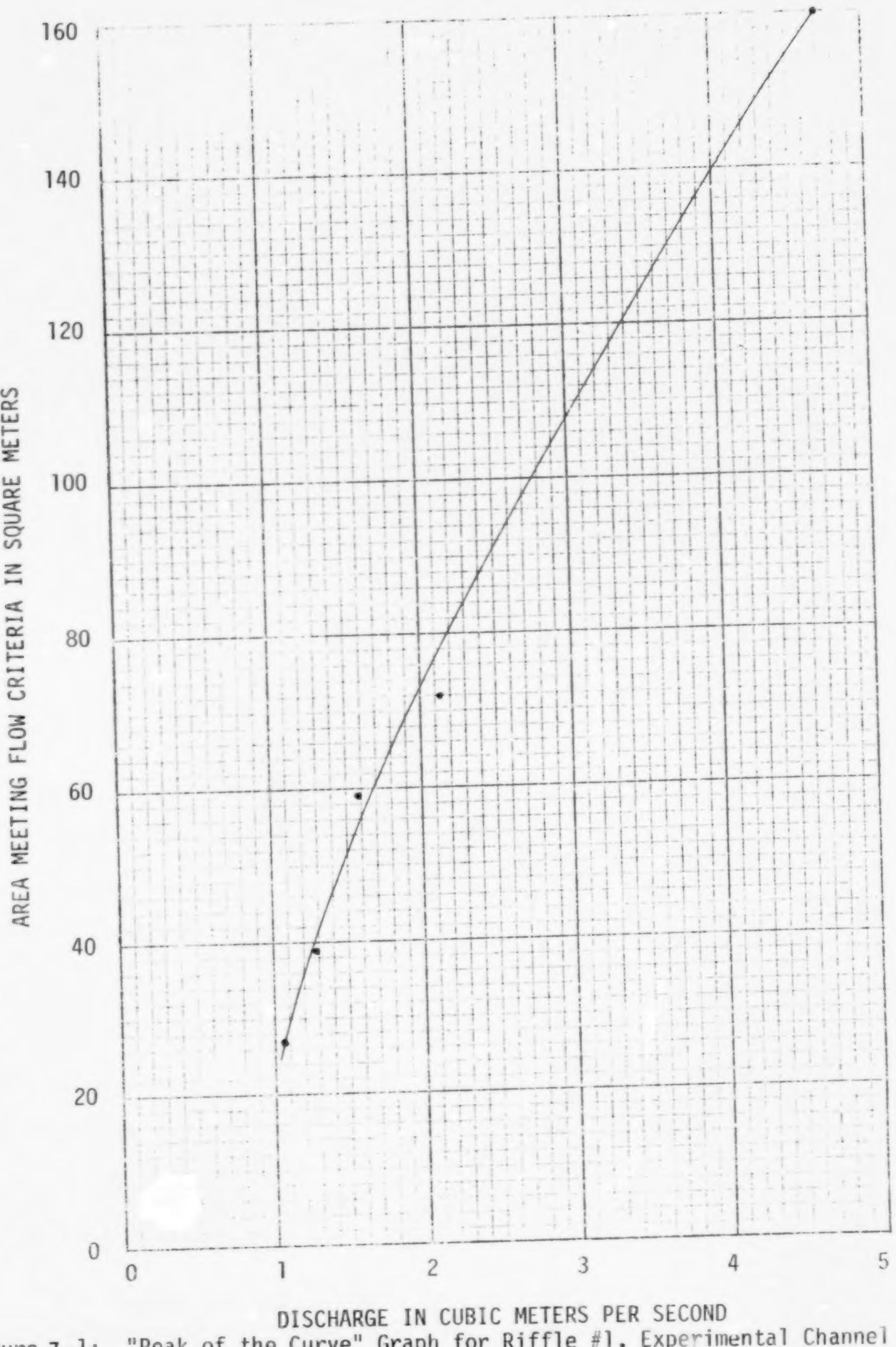

Figure 7-1: "Peak of the Curve" Graph for Riffle #1, Experimental Channel Section, Viall Ranch, from Appendix H.

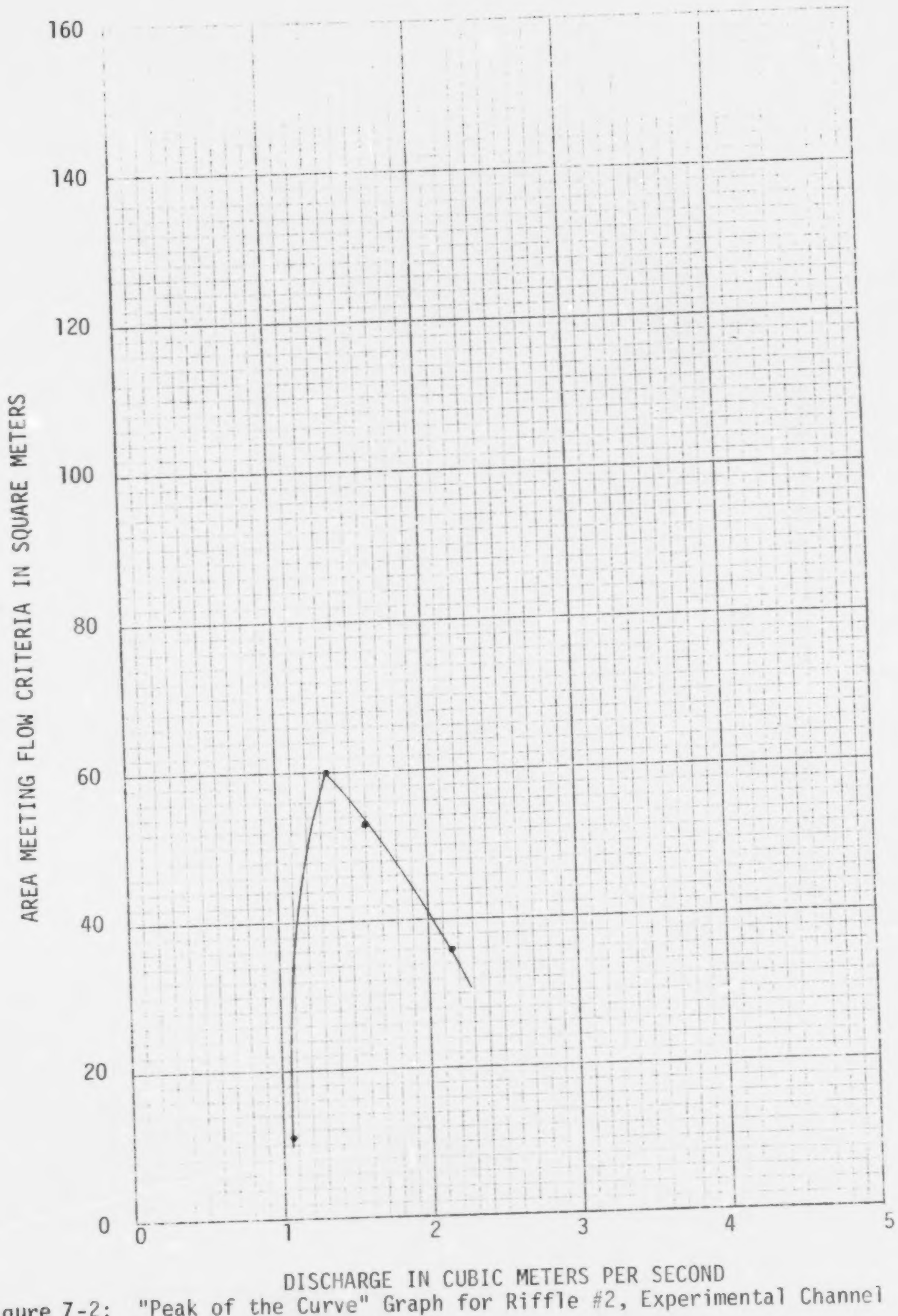

Figure 7-2: "Peak of the Curve" Graph for Riffle #2, Experimental Channel Section, Viall Ranch, from Appendix H.

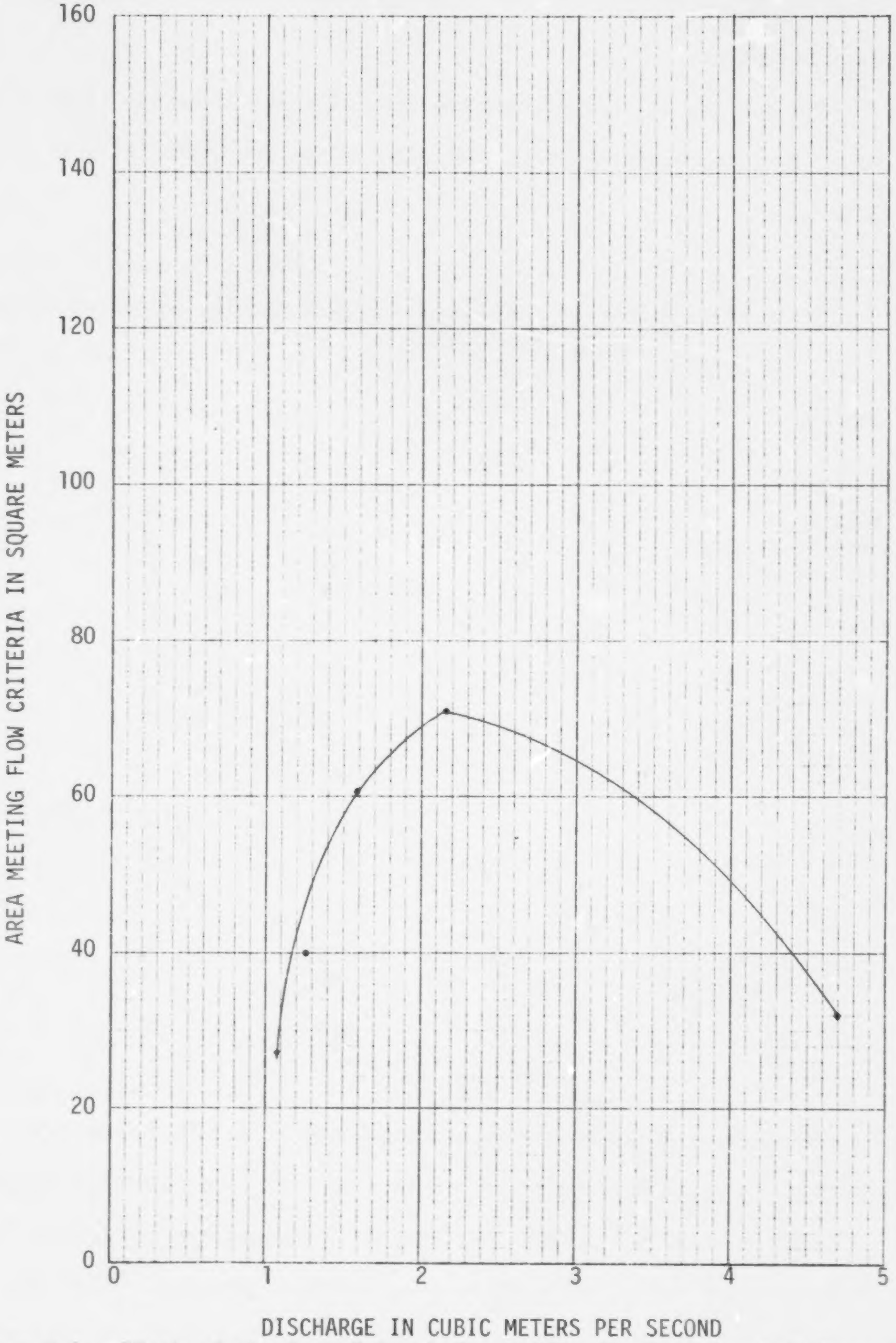

Figure 7-3: "Peak of the Curve" Graph for Riffle #1, Experimental Channel Section. Gravel substrate areas omitted.

structure that would reflect such an optimum condition. However, description of an "optimum fishery" does not lend itself to traditional means of analysis.

The results of fish collections made at a pre-diversion flow (4.70 cms.) and three experimentally controlled flows are given in Table 7-1 below:

Table 7-1: Number of Individuals of Each Species Collected at Four Experimental Flows.

Species	Flow (cms.)			
	4.70	2.01	1.33	1.07
Redhorse	5	1	6	0
Longnose Sucker	1	5	0	3
White Sucker	1	0	1	1
Mountain Sucker	0	4	1	2
River Carpsucker	0	2	0	0
Flathead Chub	11	44	67	73
Longnose Dace	1	11	11	33
Lake Chub	0	0	0	13
Silvery Minnow	0	7	0	0
Carp	0	1	0	0
Rock Bass	0	1	4	1
White Crappie	2	1	2	0
Sauger	0	0	1	0
Stonecat	0	2	6	5
Yellow Bullhead	0	0	1	0
Total Species, S	6	11	10	8

A measure of the community structure may be obtained from Table 7-1 through the concept of ecological diversity. It is a generally accepted axiom in ecology that a large environmental stress, exerted upon a diverse biological community, will result in a decrease in species diversity (Cairns, 1969). The simplest description of biological diversity is S, the number of species present. However,indices of diversity which concurrently account for both the number of species and the frequency distribution of individuals within those species, may be an indication of community structure.

Based on arguments presented by Pielou (1969), it was determined that the Brillouin index (below) was the most appropriate for the type of collection made:

$$H = (1/N) \log \frac{N!}{N_1!N_2!.......N_x!} \qquad \text{(Eq. 7-1)}$$

Where N = number of individuals in the collection.
N_x = number of individuals of each species.

Brillouin's index was calculated for each collection made, and the results are presented in Table 7-2. Because of the numerical superiority of the flathead chub in all collections, they tended to mask changes in diversity among the rest of the species. Therefore, a second calculation of H was made, omitting the ubiquitous chub from the computation. These results are also presented in Table 7-2.

Table 7-2: Species Diversity at Four Experimental Discharges.

	Diversity (H)	
Flow cms.	All species	Flathead Chubs Excluded
4.70	.463	.418
2.10	.597	.704
1.33	.484	.665
1.07	.493	.491

The differences between all diversity indices in each column of Table 7-2 are significant (t test, $p < .10$). The highest diversity occurred at a flow of 2.10 cms., although the diversity at 1.33 cms. (chubs excluded) was also quite high.

Data in Table 7-1 show that some of the changes which occurred during the course of the experiment were qualitative as well as quantitative. A deficiency of the species diversity index,when used alone, is that it is insensitive to the qualitative changes in species composition. Thus, it would be possible to acquire an entirely new fauna without significantly changing the value of the diversity index (Richards, 1976).

Figures 7-4, 7-5, and 7-6 show the distribution of fish in the experimental channel at flows of 2.01, 1.33, and 1.07 cms. These figures show quite graphically that compositional changes within the channel were more significant than were the quantitative changes.

At all flows, the community was numerically dominated by the flathead chub. However, Figure 7-4 shows that members of the sucker family were most plentiful at the discharge of 2.01 cms. In addition, pool and backwater areas were utilized primarily by suckers and minnows. Figure 7-5 shows several interesting trends. At 1.33 cms., the predicted optimum flow at Riffle 2, a substantial group of stonecats was found over that riffle. Pools and backwaters at this flow were utilized by rock bass, crappie, sauger, and bullhead, in addition to flathead chubs. Figure 7-6 shows an increasing dominance by longnose dace as water in the channel became shallower. It also illustrates a movement of the group of stonecats from Riffle #2 to the chute between Pools 3 and 4. Rock bass and other sport fish were conspicuous in their absence at reduced flow.

Because the fish had free ingress or egress to the channel during the two week acclimation period, it is assumed that the presence or absence of species indicates the suitability of habitat areas within the channel. Tables 7-3 and 7-4 show habitat areas indicated on the planimetric maps of the experimental channel.

FIGURE 7-4 FISH DISTRIBUTION IN EXPERIMENTAL CHANNEL
Q=2.01 CMS

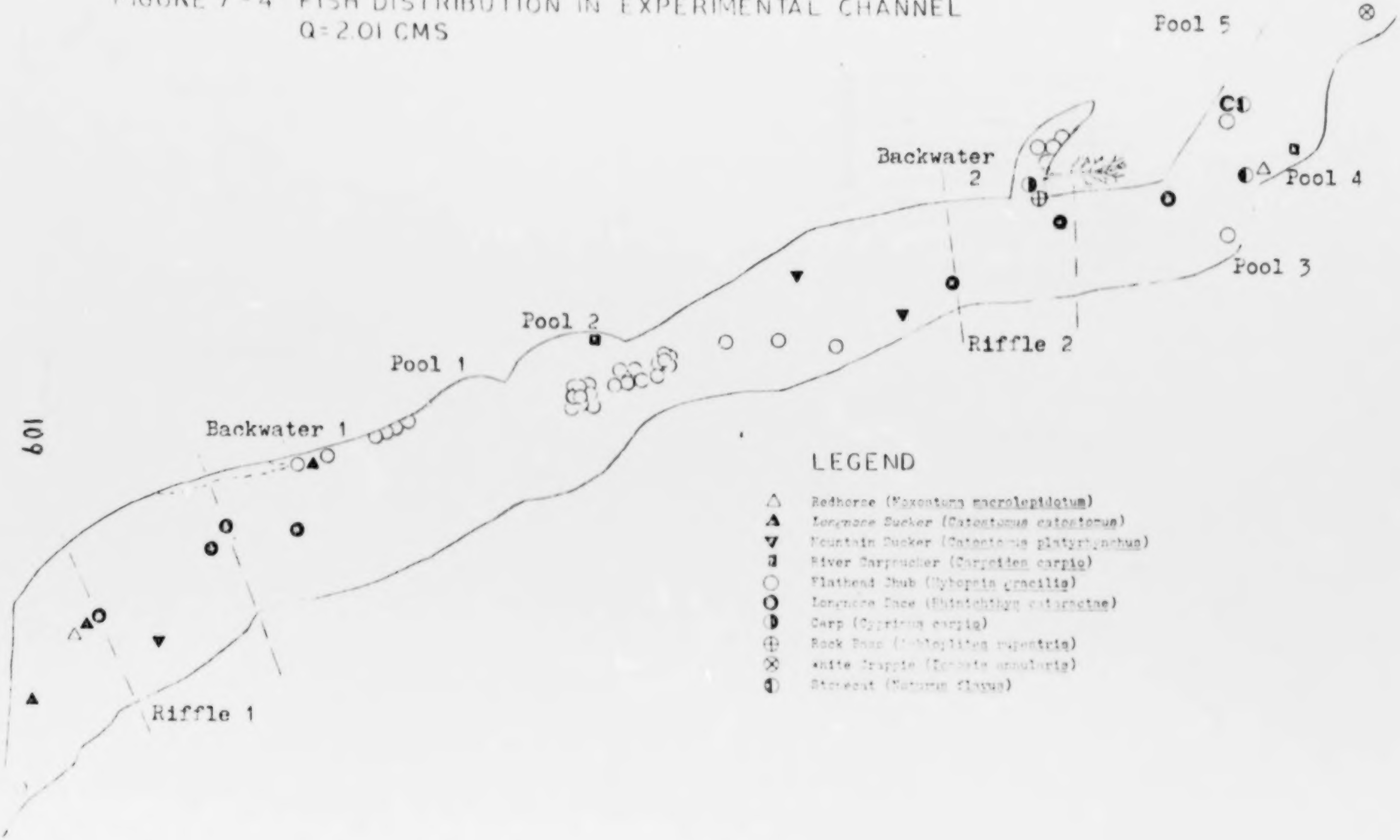
Pool 5
Pool 4
Pool 3
Backwater 2
Riffle 2
Pool 2
Pool 1
Backwater 1
Riffle 1
LEGEND
△ Redhorse (Moxostoma macrolepidotum)
▲ Longnose Sucker (Catostomus catostomus)
▼ Mountain Sucker (Catostomus platyrhynchus)
■ River Carpsucker (Carpiodes carpio)
○ Flathead Chub (Hybopsis gracilis)
● Longnose Dace (Rhinichthys cataractae)
◑ Carp (Cyprinus carpio)
⊕ Rock Bass (Ambloplites rupestris)
⊗ White Crappie (Pomoxis annularis)
◐ Stonecat (Noturus flavus)

FIGURE 7-5: FISH DISTRIBUTION IN EXPERIMENTAL CHANNEL
Q = 1.33 CMS

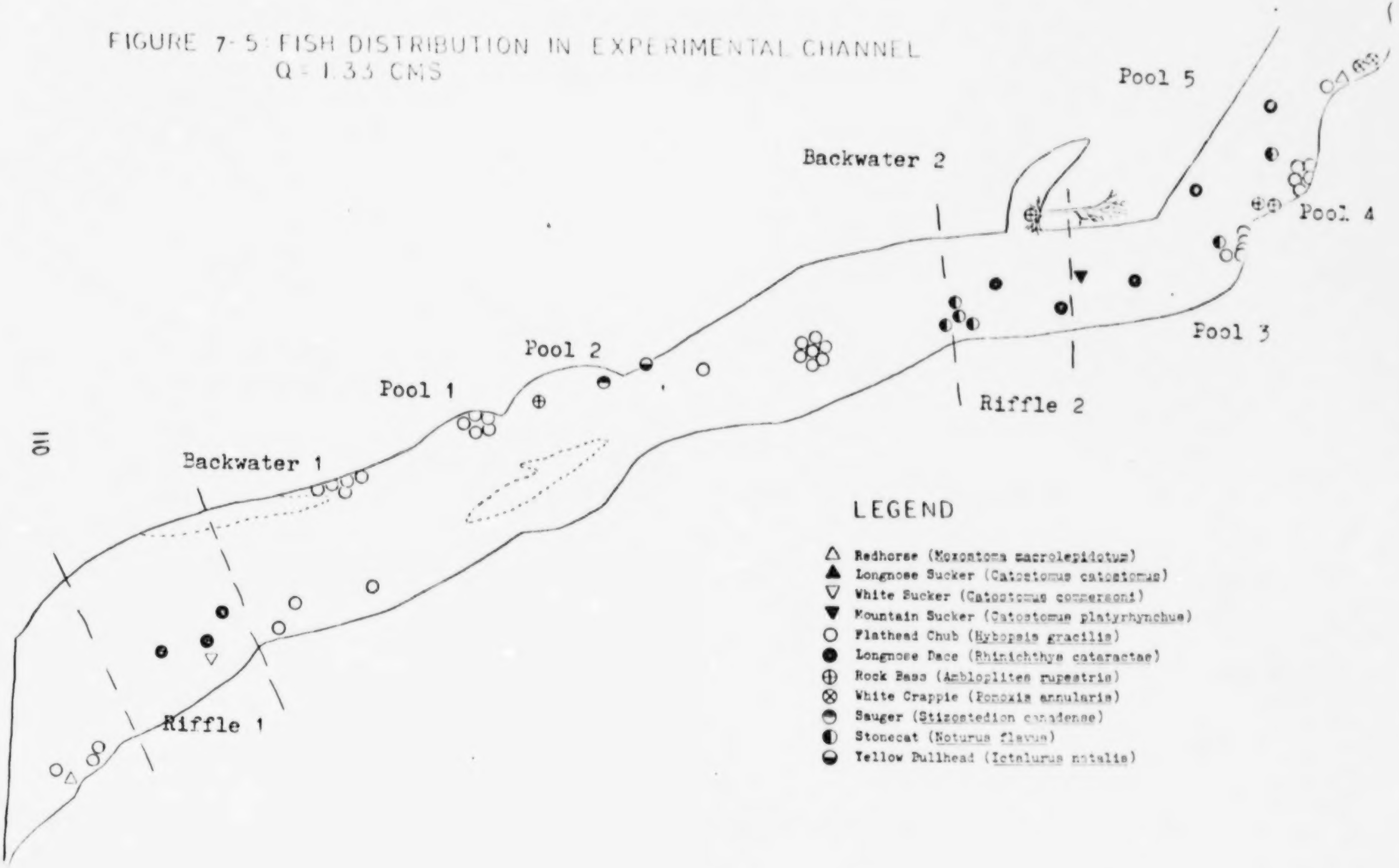
Pool 5
Backwater 2
Pool 4
Pool 3
Riffle 2
Pool 2
Pool 1
Backwater 1
Riffle 1
LEGEND
△ Redhorse (Moxostoma macrolepidotum)
▲ Longnose Sucker (Catostomus catostomus)
▽ White Sucker (Catostomus commersoni)
▼ Mountain Sucker (Catostomus platyrhynchus)
○ Flathead Chub (Hybopsis gracilis)
● Longnose Dace (Rhinichthys cataractae)
⊕ Rock Bass (Ambloplites rupestris)
⊗ White Crappie (Pomoxis annularis)
◓ Sauger (Stizostedion canadense)
◐ Stonecat (Noturus flavus)
◒ Yellow Bullhead (Ictalurus natalis)

FIGURE 7-6 FISH DISTRIBUTION IN EXPERIMENTAL CHANNEL
Q = 1.07 CMS

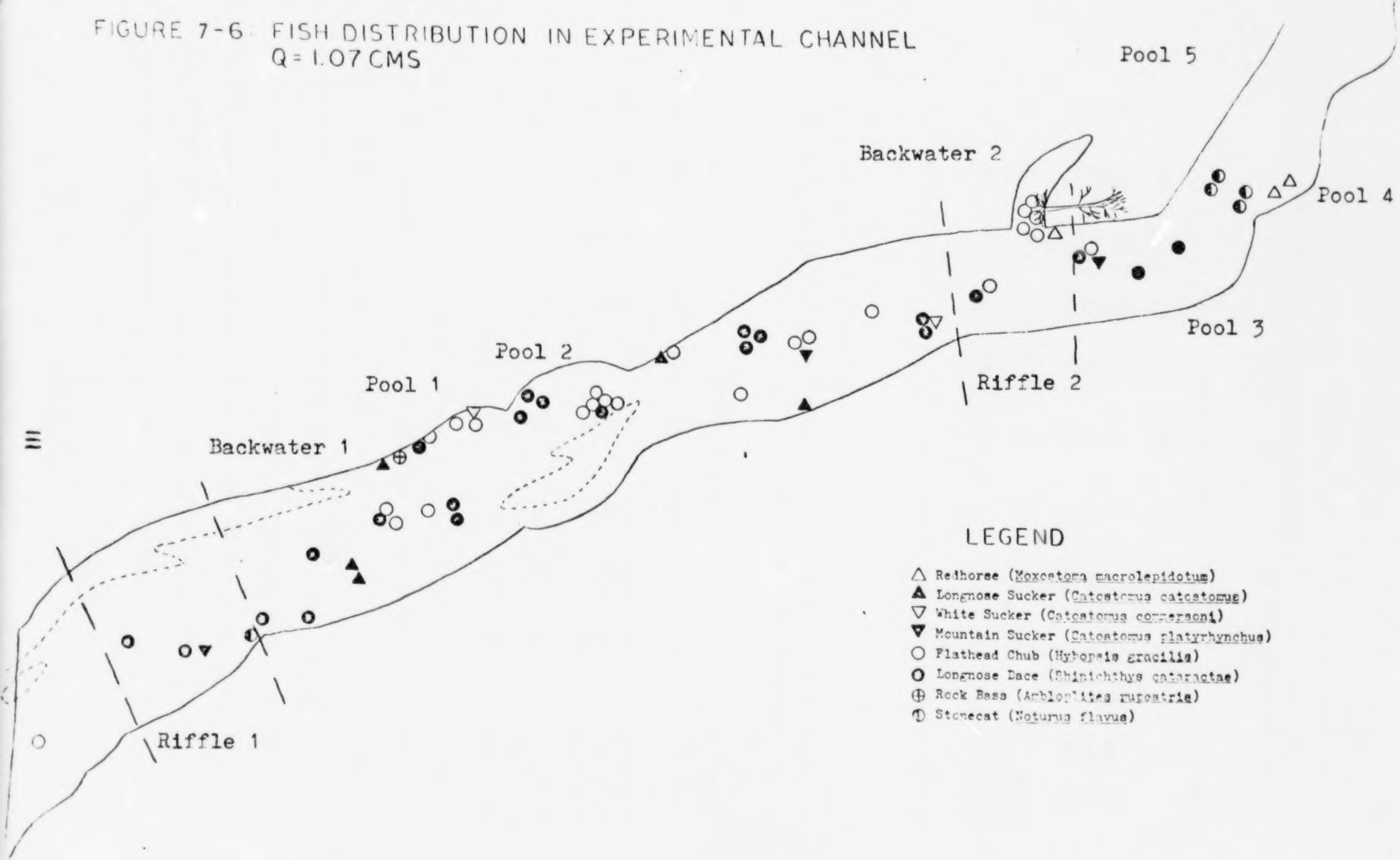
Pool 5
Backwater 2
Pool 4
Pool 3
Pool 2
Pool 1
Riffle 2
Backwater 1
Riffle 1
LEGEND
△ Redhorse (Moxostoma macrolepidotum)
▲ Longnose Sucker (Catostomus catostomus)
▽ White Sucker (Catostomus commersoni)
▼ Mountain Sucker (Catostomus platyrhynchus)
○ Flathead Chub (Hybopsis gracilis)
O Longnose Dace (Rhinichthys cataractae)
⊕ Rock Bass (Ambloplites rupestris)
⦶ Stonecat (Noturus flavus)

Table 7-3: Change in average velocity at nine habitat areas in experimental channel. Velocities in cm./sec.

Flow	Habitat Area								
	R1	R2	BW1	BW2	P1	P2	P3	P4	P5
2.01 cms.	58	73	0	0	33	32	26	20	0
1.33 cms.	47	59	0	0	32	19	20	19	0
1.07 cms.	45	58	0	0	24	15	17	19	0
Range	13	15	0	0	9	17	9	1	0
Percent Decrease	22	21	0	0	27	53	35	5	0

Table 7-4: Change in average depth at nine habitat areas in experimental channel. Depth in cms.

Flow	Habitat Area								
	R1	R2	BW1	BW2	P1	P2	P3	P4	P5
2.01 cms.	24	28	40	64	95	100	95	135	80
1.33 cms.	22	24	36	54	85	92	85	127	74
1.07 cms.	18	21	30	49	82	87	82	122	69
Range	6	7	10	15	13	13	13	13	11
Percent Decrease	25	25	25	23	14	13	14	10	14

Generally, the absolute decrease of velocity is greater than the decrease in depth in riffle areas. However, the percent decrease in depth is greater than the percent decrease in velocity in riffle areas. The reverse is true when pools and backwaters are compared. If the depth or the velocity is initially small, then a small absolute change may appear as a large percent change. Similarly, the absolute changes in velocity were generally greater in riffles than in pools, while the percent change in velocity in some pools was quite high. The absolute change in depth in pools was greater than in riffles, but the riffles showed a higher percent change in depth.

Reaction Of Aquatic Insects To Flow Reduction

From October 31, through November 3, 1975, and from November 4 through November 5, 1975, drift samples were taken to assess the effects of the closure of the Tongue River Reservoir Dam. Drift nets (mesh size 18 per cm. 30 cm. X 38 cm. orifice) were placed at the downstream end of the riffle area on the Viall Ranch section. During the sampling periods, the net contents were emptied into collecting jars of 10% formalin and water at four hour intervals. Depth of the water and current velocity at the orifice were also measured at the time of collection. The samples were later washed, sorted, identified, and counted to determine normal drift patterns and the effect of reduced flow on the drift of the stream invertebrates. It was assumed that the flow reduction would surpass those conditions of velocity and depth which cause invertebrates to enter the drift in search of new habitats.

Approximately two weeks after the apparent minimum discharge had been reached, ranging from 25 c.f.s. (.71 cms.) at the reservoir to 75 c.f.s. (2.12 cms.) at the mouth of the river, quantitative Hess samples were taken at the eight sampling stations described in Appendix D. These samples were used to determine the initial effect of the flow reduction on community structure and distribution of invertebrate species.

Diurnal periodicity of drift of the mayfly, *Baetis vagans*, had been closely examined by Waters (1962). During daylight hours, the number of individuals drifting into the nets is fairly low. However, during the night hours, the drift increases to a level ten times that of daytime drift. Waters (1965, 1966) concluded that drift was due to excessive production.

That is, drift is density dependent. Increase in density causes the displacement of smaller individuals into high current velocity areas and causes them to enter the downstream drift in search of less dense areas to inhabit. In Waters' (1972) recent review of the drift of stream insects, the effect of light on behavior patterns is also suggested as a reason for drift.

Hughes (1969 a, b) had indicated that some mayfly nymphs, particularly Baetis, orient themselves in streams by the presence of the sun (or any bright light) on their dorsal sides. The absence of this dorsal light cue causes disorientation and undirected movement which tends to add more individuals to the drift.

Elliott (1967) indicates that photoperiod has a role in causing diurnal periodicity in drift. Those individuals occuring most in the drift are night active. Being negatively phototaxic, the absence of sunlight induces foraging behavior in night active nymphs and larvae. Movement from under rocks to the surfaces of rocks not only increases the density of the individuals exposed to direct current but increases competition for available space and food on these rock surfaces. This greater competition for available resources results in greater displacement of individuals and their addition to the drift.

Bishop and Hynes (1969) believe that competative interactions play a minor role in the amount of drift and that displacement to less than optimum areas, due to increased density during night foraging, is the primary cause of drift. They do point out the role of light as a factor in their report of depressed drift during periods of moonlight, as had been previously reported by Anderson (1966).

Minshall and Winger (1969) have shown that a sudden reduction in stream flow will result in an increase in invertebrate drift. The main cause of this increased drift in response to changes to other than optimum conditions of velocity and depth. If the streamflow reduction is sufficiently rapid, normal avoidance response to light will not occur and drift will increase during daylight hours as well.

Pearson and Franklin (1969) believe that water level fluctuations affect drift by altering the population density at any given point and by affecting the amount of light penetrating to the substrate.

Lemkuhl and Anderson (1972) agree with previous statements that volume of flow and microdistribution are the primary and inter-related causes of drift in aquatic ecosystems. However, they suggest that drift is a species specific response and that information on drift of a few representative species cannot be extrapolated to generalizations about all insects.

As can be seen by Figures 7-7 through 7-11, drift of stream invertebrates in the Tongue River does exhibit a diurnal periodicity. Of particular interest is the fact that the night samples, in addition to containing increased numbers of mayflies, has as its main component, large numbers of standing water forms, especially the hemipteran *Graptocorixa* and the coleopterans *Gyrus* and *Dytisca*. This diurnal periodicity of Hemiptera and Coleoptera is previously unreported. Solar cues for orientation and foraging may also play a great role in maintenance of position in still water along the edges of the river. Removal of solar cues may cause movement into running water and addition to the drift.

Drift increased dramatically after reduction of the level of the river by 3 cm., representing a change in discharge from 190 c.f.s. (5.38 cms.) to approximately 130 c.f.s. (3.68 cms.). Although a diurnal period was maintained as the river level dropped (approximately 3 cm./day during the sampling period) the pattern is on an elevated scale. Greater numbers appear to be drifting during the day as well with massive drift occuring during the night hours.

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Figure 7-7: Drift during the period of flow reduction, all invertebrates. Dam closure on October 30, 1975. Sampling begun on October 31, 1975 and ended November 4, 1975.

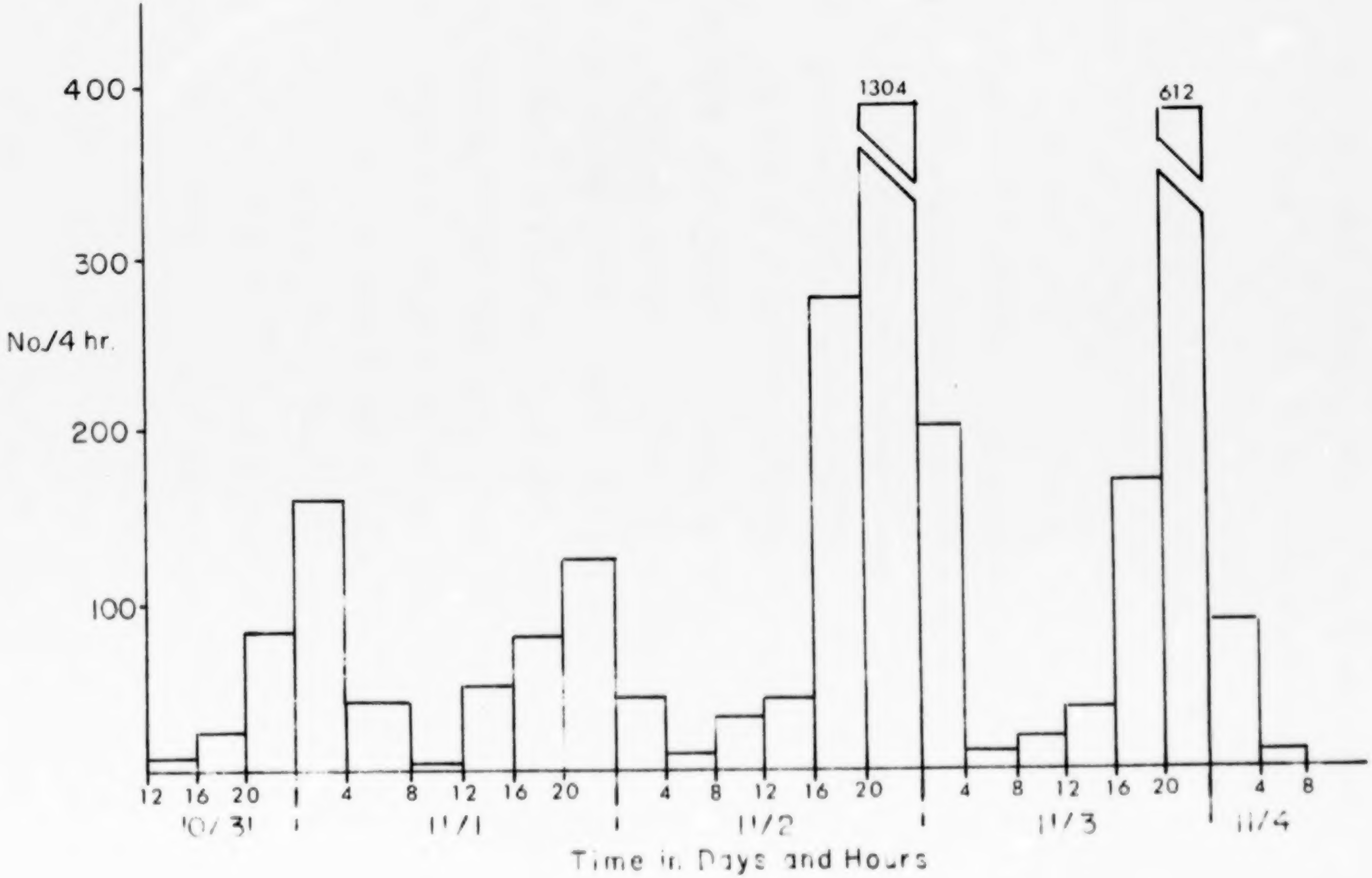


Figure 7-8: Drift during period of flow reduction, Ephemeroptera. Dam closure on October 30, 1975. Sampling begun on October 31, 1975 and ended on November 4, 1975. Dashed area represents contribution of Rhithrogena to drift.

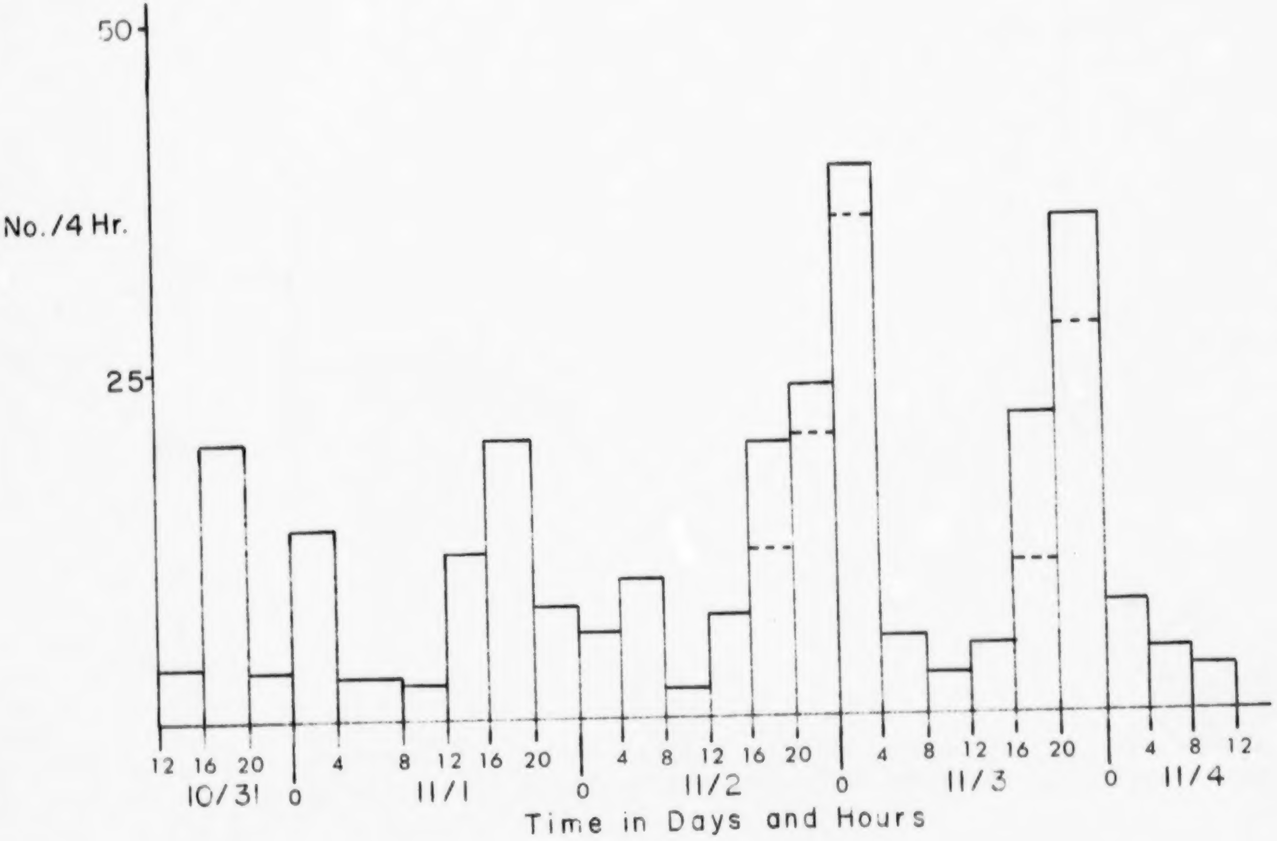


Figure 7-9: Drift during period of flow reduction, Plecoptera. Dam closure on October 30, 1975. Sampling begun on October 31, 1975 and ended on November 4, 1975.

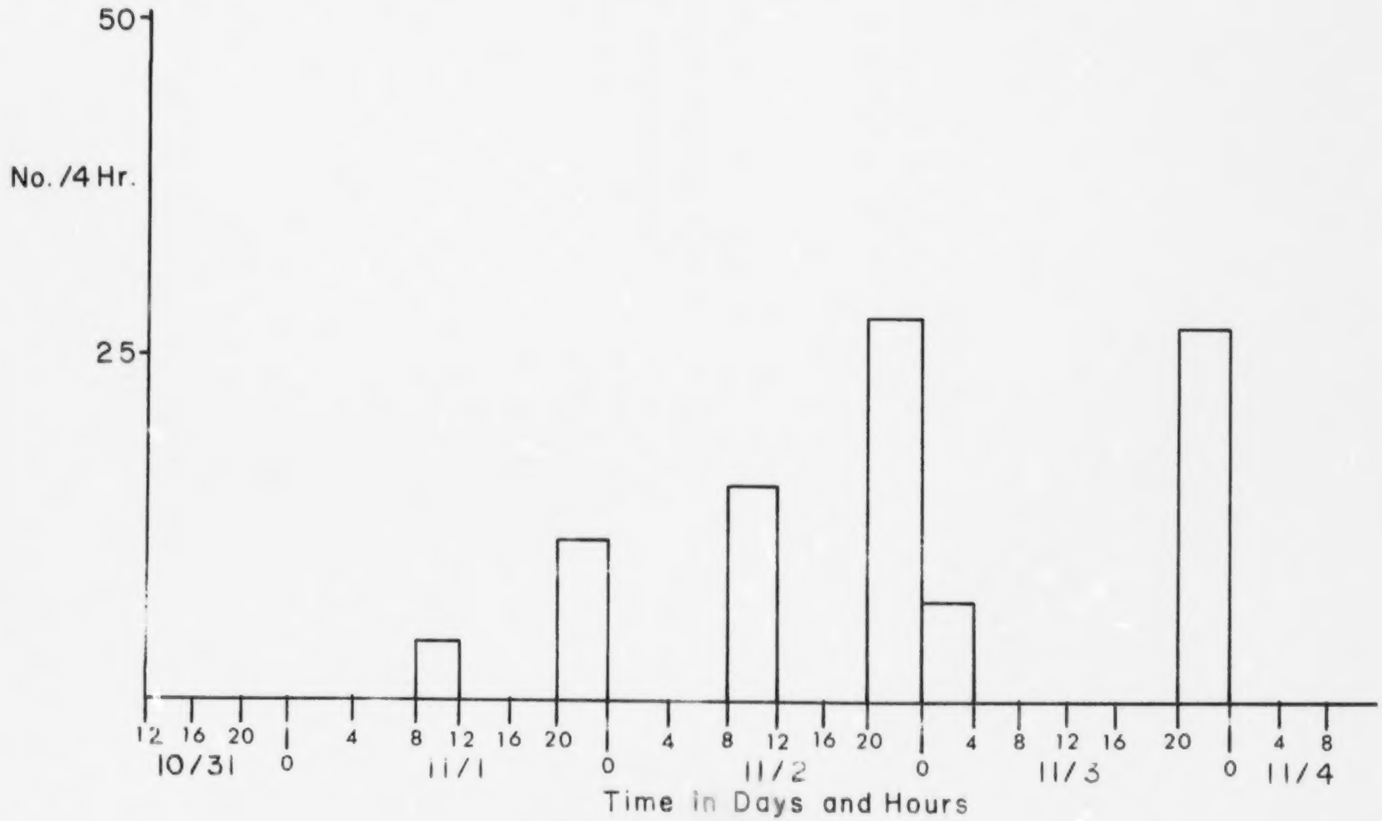
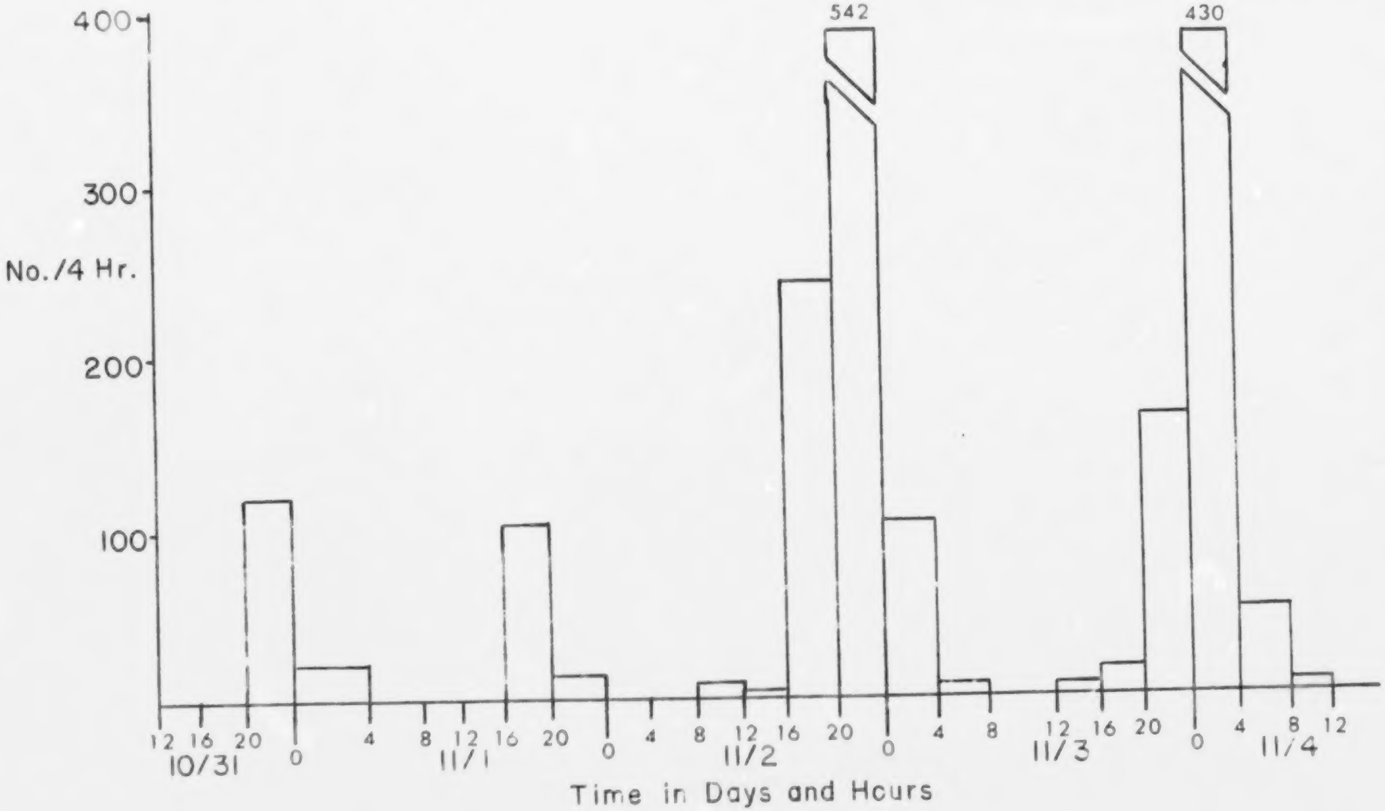


Figure 7-10. Drift during period of flow reduction, Hemiptera. Dam closure on October 30, 1975. Sampling begun on October 31, 1975 and ended on November 4, 1975.



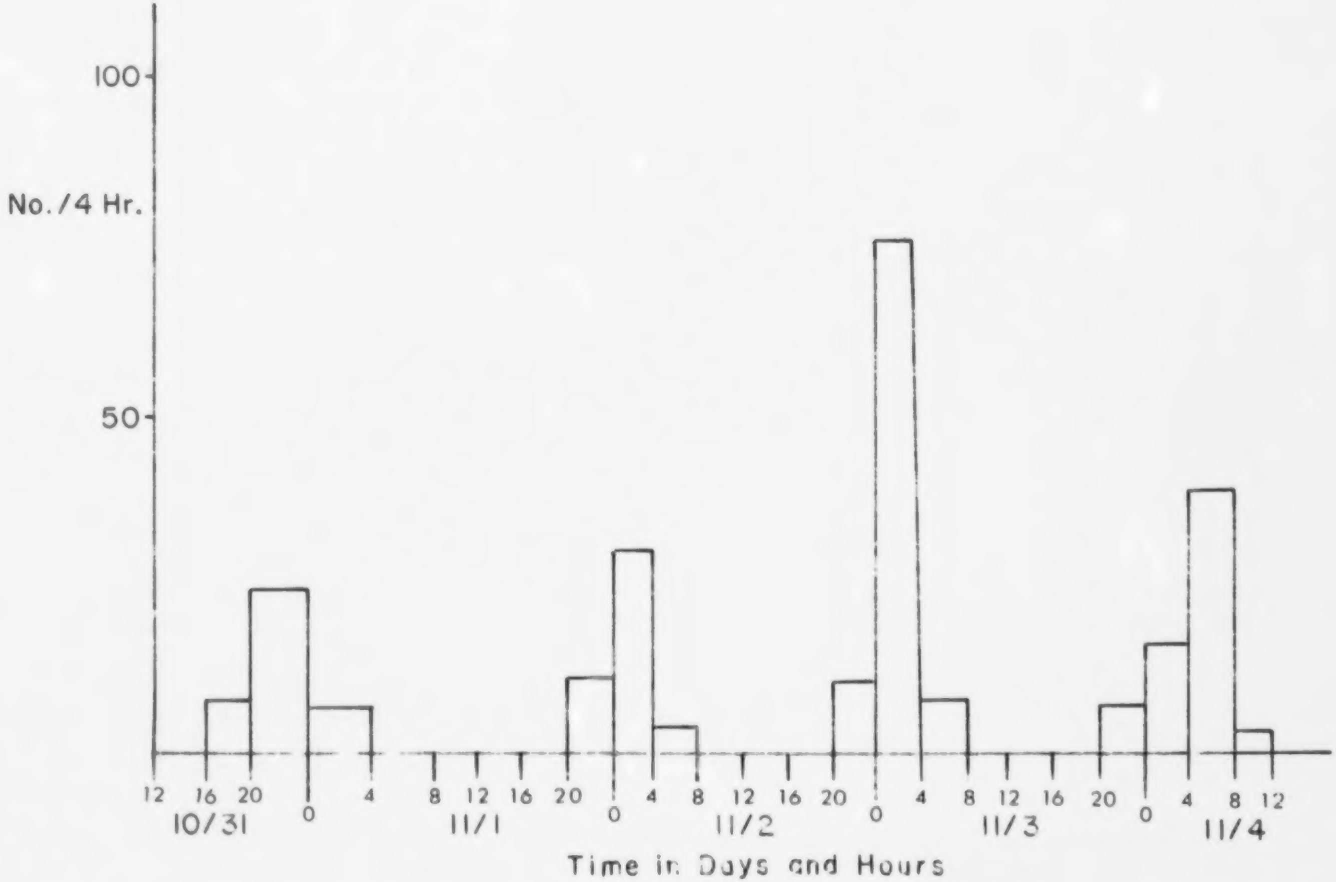


Figure 7-11. Drift during period of flow reduction, Coleoptera. Dam closure on October 30, 1975. Sampling begun on October 31, 1975 and ended on November 4, 1975.

The constant drop in water level was apparently not sudden enough to cause massive daytime drift. However, it probably caused considerable lateral movement with narrowing stream width. Lateral movement may cause an increase in density of invertebrates in a given area which would be exhibited by increased drift during the day and especially at night when foraging takes place. Displacement of individuals to less than optimum foraging areas, depth,and velocity conditions would be considerably higher than under normal circumstances.

The fact that massive drift began when stream discharge was reduced to between 130 c.f.s. (3.68 cms.) and 110 c.f.s. (3.12 cms.) indicates that minimum discharge, to maintain optimum streamflow requirements for benthic community, has been reached. Thus, on the basis of drift information, it would be appropriate to recommend that a discharge of 130 c. f.s. (3.68 cms.) be maintained as a minimum in the channel of the Tongue River.

The presence of young-of-the-year of the stonecat (Noturus flavus), which has been recommended by Bovee (1975 a,b) as an indicator fish species, in the samples from hours 0000 to 0400 on the nights of November 3rd and 4th, indicates the probable attainment of minimum discharge for maintenance of the fish community as well.

The fact that the positive phototaxis of Rhithrogena (as noted by Elliott, 1967) has been overcome and that this species also increased in drift samples after 130 c.f.s. (3.68 cms.) flow had been reached, supports the other evidence that Rhithrogena would be a good indicator species.

A community association dendrogram and abundance kite diagram are presented in Figures 21 and 32 of Appendix D. The dendrogram indicates that, as a result of the dewatering of the Tongue River, the association (similarity) between communities has increased and approaches homogeneity over the length of the river, although distinct communities remain. The distribution of the organisms in comparison with previous fall samples (see Figure 3, Appendix D) has been dramatically changed. The overall effect has been to displace many of the species downstream a distance of 40 to 120 km. (25 to 75 miles).

In other species, the reduction has had the effect of increasing the range of the species over the length of the river. As representative examples, Rhithrogena hageni had its downstream limit extended from Station VI to VII; Paraleuctra sara had been displaced downstream three stations; Capnia limata was only found at Station V rather than III and IV; the downstream limit of Isogenoides frontalis was extended to the mouth of the river; Cataclysta has moved from Station III to Station VII, and Metriocnemus increased its distribution over the length of the river.

Dugesia tigrina became the dominant individual in the cold water section of the river. The molluscs are considerably reduced, possibly reflecting the concentration of Dugesia, a mollusc predator, and the inability of rapid lateral migration in order to remain in the running water area. A dominant is not apparent in the middle section of the river; however, Rhithrogena and Strophoptery are quite abundant. In the lower river, the overwhelming dominant is Ephemerella. Due to decreased turbidity (less suspended food material) and less than optimum conditions of current velocity for the proper construction of trap nets, Cheumatopsyche, formally dominant in the lower part of the river, has been greatly reduced in number (Compare Kite diagrams for Cheumatopsyche on pages D-45 and D-60).

Comparison of numbers of individuals in samples before and after closure of the dam indicate that densities of the samples have increased to a considerable degree. Most samples taken during the closure period show density increases to be threefold or more. Since it was impossible to obtain continuous drift samples during closure, due to nightly formation of anchor and frazil ice, it is not known whether drift conditions had returned to their normal diurnal patterns. Thus, a maximum macroinvertebrate density can not be estimated. One can assume, however, that since the width of the river was reduced to 7 meters from an average width of 30 meters, the overall number of invertebrates in the river have also been reduced as a result of increased drift and decrease in habitable substrate surface area.

Discussion Of Methodology And Field Techniques

To be judged reliable, a methodology must meet two basic criteria. First, it must have a high degree of reproducibility; results obtained from one part of the river should not differ substantially from results obtained in another part, for the same biological function. Secondly, results obtained by application of the method must agree with actual observations and measurements in the field. It is the purpose of this section to discuss the validity of the methodology, identify limitations and areas of inadequacy, and recommend procedures to increase the reliability of the methodology.

Perhaps the most serious deficiency of the methodology most widely used to date is the recommendation of a minimum fisheries requirement based on some percentage of the optimum flow. In most cases of in-stream flow recommendations, the determination of the optimum flow is irrelevent to the problem. When streamflow is adjudicated, it is highly unlikely that fisheries will be allocated an optimum flow. Likewise, the definition of a minimum streamflow as a percentage of the optimum flow must be subjective, and is therefore unjustified. The criticisms raised by Milhous (1973) are valid, and are essentially a result of this subjective definition of the minumum flow. The selection of a recommended rearing flow as 75% of the optimum would require a minimum rearing flow of around 9 cms. (320 c.f.s.) for the Tongue River, for example. From the flow duration curve for the Tongue River (Chapter 1), it can be seen that natural streamflow was less than 9 cms. about 60% of the time for the water years 1961-1970.

Milhous (1973) suggests that this problem may be overcome by the definition of a "base flow." His definition of the use of the base flow concept is as follows:

> "There shall be a flow in perennial streams which preserves certain values and the remaining available water shall be allocated among competing uses and users on the basis of maximum net benefits. In the case of fisheries, this means that a survival flow will be in the stream, but the flows to maintain the fishery above the survival level shall be part of an allocation of waters on the basis of maximum net benefit."

In other words, water volumes above preservation flows (i.e. enhancement flows) must compete with other beneficial uses of the water. Unfortunately, the definition of the survival flow is critical, with little room for error. It is here proposed, that the "base flow" as defined above, may be accurately and reliably determined by the Indicator Species-Critical Area methodology. "Base flow" may be defined as that discharge which first provides some increment of preferred area for the indicator species, over the critical area. For the Tongue River, base flow was determined to be 2.83 cms. (100 c.f.s.), using the stonecat as the indicator species. However, when Rhithrogena hageni is used as the indicator species, it can be shown that the extinction point for flow criteria occurs somewhere between 3.70 and 3.85 cms. (See Appendix C). This flow was equalled or exceeded about 75% of the time for the water years 1961-1970 (Hopkins, 1973). Therefore, the base flow concept meets the criteria of water availbility.

Experiences provided from the experimental channel and from the studies of aquatic insect drift, confirm that there is a definite relationship between streamflow, community structure and productivity. While it is probably impossible to predict with any methodology the absolute minimum water volume requirement of the ecosystem, it was possible to determine the base flow requirement within 0.3 to 0.5 cms. using the Indicator Species-Critical Area Method.

It was shown that once the flow falls below the base flow level as predicted by the metholology, both insect and fish communities may be considerably altered. Flows of less than 3.68 cms. in the main channel of the Tongue River resulted in a ten-fold increase in the number of aquatic insects in the drift. Concurrently, there was a three-fold increase in the density of insects. This result is interpreted as a net decrease in the carrying capacity of the river, with a resultant decrease in insect productivity.

Changes within the fish community are possibly not as dramatic as those within the insect community. However, the changes indicated by the experimental channel are the type which might result in an undesirable recreational fishery. As the flow in the experimental channel fell to the base flow level, the diversity of the fish community declined significantly. This decline in fish diversity was accompanied by a qualitative species shift, trending toward domination by suckers and minnows and the displacement of sport and game fish. Such a shift is likely to decrease the quality of recreational fishing in the river.

Reproducibility:

Reproducibility as used here is a characteristic of a methodology or procedure which results in comparable data between one area of the river and another, for the same biological function. Several factors must be considered to ensure high reproducibility with this methodology.

The most important of these considerations is the number of discharges which must be mapped to adequately define either the optimum or the base flow for a given indicator species. For example, the Viall section was mapped at seven different discharges, the Orcutt section at only five. As a result, the optimum flow at the Viall section is more clearly defined than for the Orcutt section for both the stonecat and for *Rhithrogena*. The optimum flow for *Rhithrogena* was probably not mapped at the Orcutt section, since the optimum flow curve does not show a sharp peak. When the base flow concept is used, it is particularly important that sufficient data be collected at the lower end of the optimum flow curve. This procedure could provide a considerable time and manpower savings, but may require some a priori concept of what the base flow looks like. Unnecessary or unimportant measurements may be eliminated by constructing the maps for each set of data as soon as possible after it is taken. This makes it possible to determine if either the optimum or the base flow is being approached. As a rule of thumb, five discharges are sufficient to approximate the optimum or base flow, but up to ten may be required for good resolution.

It was determined from the experimental channel studies that site selection may significantly affect reproducibility. Controls should be carefully selected, and sections with shelves or gravel bars should be avoided unless these areas are defined as critical areas, as is the case when spawning flows are determined.

Controls should extend completely across the river, at approximately a right angle to the direction of flow. Many stream controls, however, tend to be arcuate and non-perpendicular to flow. The use of multiple transects makes it possible to include the entire control area in a map, whereas single transects frequently miss a sizeable portion of the control.

Reproducibility may also be affected in the computation of the discharge from the mapping data. Computation error may be compounded if the same measurement errors are made at two different sites. If there is a U.S.G.S. gaging station nearby, the discharge may be obtained from a rating table for the station. However, if the discharge is computed from mapping data, computation error may be reduced by establishing at least one of the transects above the control, and using data from that transect to calculate the discharge. In most cases, the control itself is non-uniform in cross section and velocity, conditions which are not conducive to good discharge measurement. However, in following the above recommendations, the multiple transect method can be expected to give highly reproducible results.

Limitations:

A frequently raised objection to multiple transect methodology deals with the large time and manpower investments required to obtain and synthesize the field data. Approximately three man-days are required for the acquisition of field data and construction of hydrologic maps for each discharge and critical area measured. An additional time requirement can occur in waiting for a sufficient change in discharge to justify remapping a section.

Both types of time and manpower requirements may be significantly reduced through the use of the flow prediction models presented in Chapter 6. The Water Surface Profile Program, used in conjunction with the CONTOUR Program can accurately and reliably supply the data needed for planimetric mapping, with an approximately 60% work-time reduction for data collection. The time requirement for the construction of planimetric maps may also be reduced through the use of computerized contouring plotters, such as the Cal Comp plotter. The potential savings in work-time with the use of such plotters may be as large as 95% (one day for the plotter as compared to around 20 days for hand-drawing) for each critical area. Therefore, it may be possible to reduce the total time requirement for implementing the methodology from its present 6 to 8 month requirement to as little as one month. This potential for savings most certainly warrants further investigation into the use of flow prediction models and plotter programs.

Perhaps the second-most frequently raised criticism of multiple transect analysis is that it must be restricted to small, wadeable rivers. This restriction is probably unjustified. The U.S. Geological Survey has made current meter measurements from boats for years (Carter and Davidian, 1968). Special equipment, such as bomb weights and cable booms would be required, but such equipment is neither rare nor expensive. Even the use of the troublesome tagline may be eliminated with electronic distance meters such as the Hewlett-Packard 3800 B (Paily and Macagno, 1976).

Another possible limitation to the methodology is in the selection of indicator species. As originally conceived, the Indicator Species-Critical Area Method was designed to allow researchers to concentrate their efforts on a few species, and a few habitat areas, rather than diffusing their efforts over the entire river length and fish community. The underlying premise of the methodology is that stream velocity is affected more than depth with reduced streamflow. This premise appears to hold true formost streams. Therefore, an ideal indicator species should be velocity limited rather than depth limited. The composite maps in Appendix B show that the stonecat's preferred area decreased more rapidly due to insufficient depth than because of insufficient velocity. Conversely, Appendix C shows that Rhithrogena *hageni* was restricted more by loss of velocity rather than depth. It is suggested that *Rhithrogena hageni* is probably a more sensitive indicator species than *Noturus flavus*.

Both the stonecat and *Rhithrogena* appear to be ubiquitous in most NGP rivers. An advantage of using *Rhithrogena* as an indicator, as opposed to some other fast water species, is that it is relatively long-lived, and may be found in its nymphal stage at virtually any time of the year. In the absence of *Rhithrogena* other fast water species may be used as indicators. Examples of these alternate species are *Ephoron*, *Traverella*, or *Iron* of the order Ephemeroptera.

Other fish species may show more current dependence than the stonecat, and the search for an ideal fish indicator should not be abandoned now. Investigations should include the mountain sucker, the longnose dace, and possibly the sturgeon chub. Until flow criteria can be established for these species, it is recommended that *Rhithrogena hageni* be utilized as the rearing indicator species.

Continuing research is needed into the determination of spawning flow criteria and indicator species. The criteria established for the sauger and shovelnose sturgeon during this study should be considered only tenative. A great deal of pertinent information concerning spawning criteria remains to be collected. Increased water volumes and turbidity seriously impair the ability to sample the spawning fish population. Sampling in the spring of 1976 showed that concentrations of fish do not necessarily equate with spawning, particularly if the number of ripe or running females is small. It may take several years of data collection before sufficient information is gathered to show definite flow preferences by spawning fish. However, these constraints should not deter researchers from attempting to define such criteria.

Additionally, there appears to be an almost steady procession of different species utilizing the same critical areas for spawning during the course of the spring. Elser (1976) suggests that several indicator species be used to resolve this problem. During the early rising stage of the spring runoff, the sauger is the primary spawner. Later, as the runoff approaches its peak, the shovelnose sturgeon begins its spawning activity. The channel catfish is among the last species to spawn, apparently during the falling stage of the spring runoff. Each of these species was commonly found in fast to very fast water (especially the sturgeon), supporting the hypothesis that they may be good velocity limited indicators.

The selection of critical areas for spawning should purposely include areas of gravel bars and shelves. Many species, including the sauger and shovelnose sturgeon, select gravel bars as preferred spawning areas. There is also an important hydrologic reason for using gravel bars as critical areas. At the Ft. Keogh site, most of the water at low flow tended to be concentrated in the thalweg. Therefore, in order to meet even the shallowest passage requirements, the velocity of the water was very high, even at low flow. When the gravel bars were flooded they afforded areas of relatively slower water, which facilitates the passage of migrating fish. At lower flows, migrants are forced to swim against the much stronger current in the thalweg.

The base flow for spawning, using the shovelnose sturgeon as indicator, may be found by examination of the spawning composites in Appendix F, and the discharge-preferred area curve in Figure 7-8. The scour pool near the left bank of the sampling site was not considered to be part of the critical area because it showed relatively little hydrologic change at different discharges.

Suitable hydrologic conditions first occurred over the gravel bar, considered to be the critical area, at a discharge of 13.0 cms. At this same discharge an inflection point occurs on the discharge-preferred area curve (Figure 7-7). Therefore, it is recommended that 13.0 cms. be considered the base spawning flow for the shovelnose sturgeon. In terms of water availability, it is not realistic to compare the base spawning flow with the annual flow duration curve, for a 13.0 cms. flow is only exceeded about 20% of the time. Rather, water availability should be based on the return period of the high spring runoff. Figure 7-12 shows that there is an 86% probability that a June base flow would equal or exceed 13.0 cms., based on streamflow records for the water years 1961 through 1974.

A final limitation, perhaps the most important, deals not with the methodology, but with the philosophical concept of "in-stream flows" itself. There are many legal and socio-economic ramifications which must be resolved before a water use policy, giving full consideration to in-stream needs, can be established.

It has become apparent that among the competing uses of water, in-stream needs consistently occupy the lowest priority position. If irrigation, municipal, and industrial uses all have higher priorities than in-stream needs, then it seems reasonable to believe that in-stream requirements will receive only whatever water is left over. Should this be the case, there appears to be little justification for establishing any in-stream flow requirements regardless of the methodology.

The only practical exception to this argument appears to be the use of reservoir releases to ensure an in-stream flow. In this case, the question arises: "Who pays for the storage to be eventually released to maintain in-

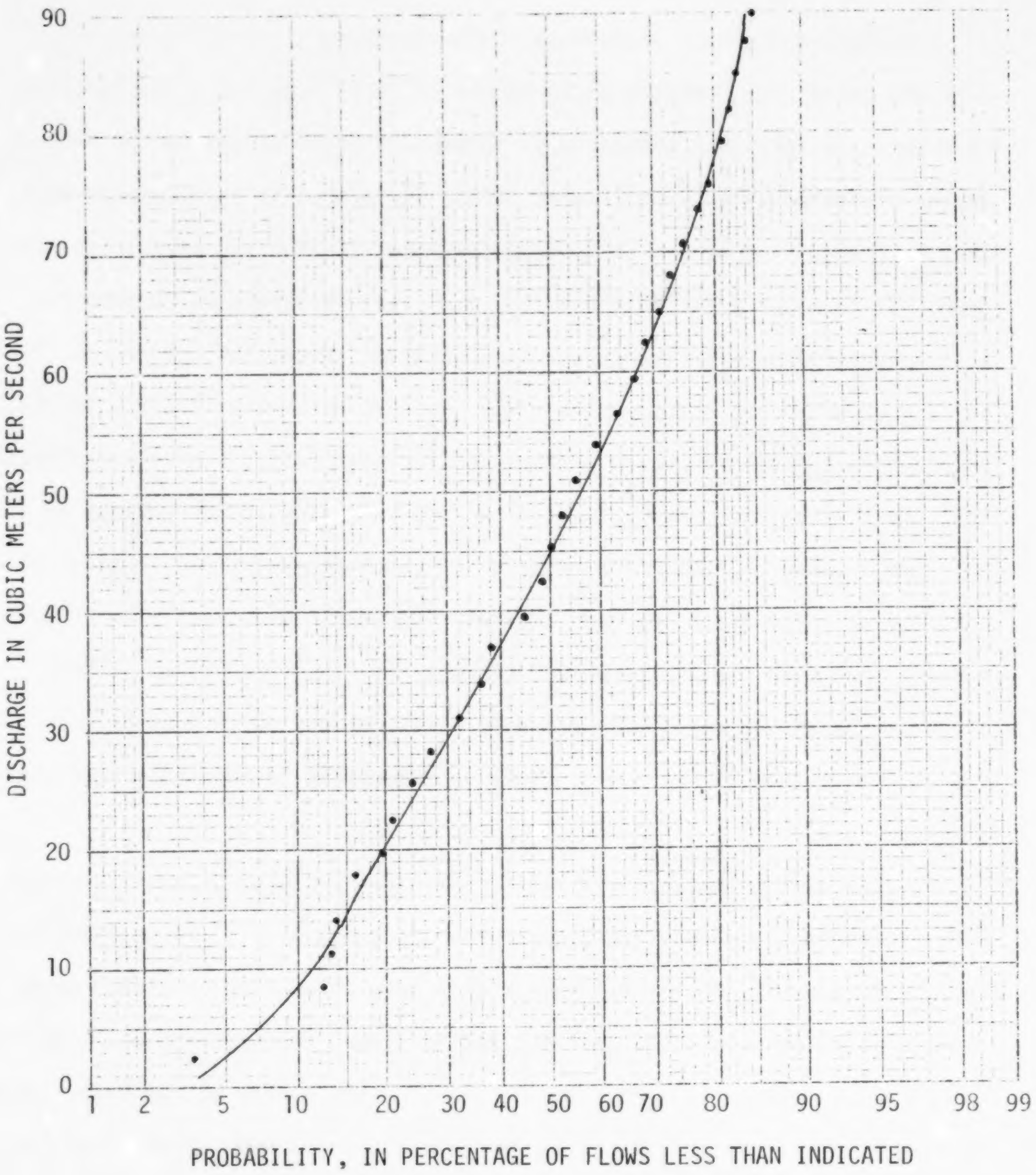


Figure 7-12: Cumulative distribution curve of June streamflow in the Tongue River at Miles City, 1961-1974.

stream flow?" Should the public pay for public water to remain in the channel, or should the water users be required to pay for depletion of a public resource? These questions must be answered before a course of action can be affirmatively taken. The state of the art for determining in-stream needs appears many years ahead of our ability to ensure that these flows will remain in the channel.

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CHAPTER 8: ICE FORMATION

Mechanics

Despite the common occurance, and biological and economic importance of ice formation in rivers, relatively little is known concerning the process of ice formation or its biological effects. Several types of ice commonly occur in rivers at various stages of freeze-up, and there may be some confusion between the various forms. Schaefer (1950) gives a good description of the three principle forms of ice found in rivers.

Frazile ice crystals are thin, circular disks showing no visible evidence of the trigonal symmetry common to snow crystals. These crystals range in thickness from 25 to 100 microns, and from 1000 to 5000 microns in diameter. They are apparently surface-formed crystals which occur whenever bulk water is supercooled, and may often be seen forming small rafts of floating skim ice. Whenever turbulence is encountered, many particles can become submerged, leading to a false impression that frazile ice forms primarily in turbulent riffle areas. During the early stages of freeze-up, frazile ice forms on practically the entire river surface. However, riffle areas remain open long after surface ice has formed on other parts of the river, and are prime producers of frazile ice during intermediate freeze-up.

When an object, such as a rock or tree root, is submerged in water containing frazile ice, the crystals collect on the upstream side of the object. This results in an underwater buildup of frazile ice crystals in large sponge-like masses. These masses may easily be mistaken for anchor ice.

Anchor ice consists of sheet-like crystal aggregates of ice which grow out from submerged objects. Anchor ice is thought to form as a result of radiational cooling of the streambed (Barnes, 1926), and therefore forms in similar manner to frost forming on terrestrial surfaces. Cold, clear nights are required for good anchor ice formation, whereas cold temperatures alone are sufficient for frazile ice formation. Schaefer (1950) suspects that many of the formations previously reported as anchor ice were in fact structures formed by the shingling effect of frazile ice particles.

Surface sheet ice is first formed when pans of floating frazile ice crystals jam together and adhere to the bank and other pans of ice. Areas of rapid and turbulent water tend to remain open during this freeze-up period because the ice crystals remain in suspension, rather than floating to the surface. Once a continuous layer of surface sheet ice has formed over an area the formation of frazile ice ceases, although areas of open water will continue to produce frazile ice indefinitely. Thickening of the ice sheet proceeds primarily through conduction of heat through the ice sheet.

Barnes (1906) describes the thickening rate by conduction alone, by the formula:

$$t = \frac{LSE}{K\,\theta}\left(1 + \frac{E}{2}\right) \qquad \text{(Eq. 8-1)}$$

where t is the time in seconds for the ice sheet to attain a thickness E, in cm; L is the heat of fusion, 79.7 cal/gram; S is the density of ice, .9166; K is the thermal conductivity of ice, 0.0057 cal/°C difference of temperature per square centimeter per second; and θ is the temperature difference between the under side of the ice sheet (0 °C) and the air temperature. This formula assumes that the surface is clear of snow, and does not consider advected heat losses or gains. According to this formula, the ice sheet over a river should be of uniform thickness along a cross section, or between areas subject to the same atmospheric conditions.

During the winter of 1975, the ice thickness was measured over cross sections at the SH Ranch, the Viall Ranch, and the Birney section. These measurements are illustrated in Figures 8-1, 8-2, and 8-3, respectively. Current meter measurements, made through the ice, indicated that there is an apparent relationship between current velocity and the thickness of the ice cover. A least square regression line was calculated for the three cross sections measured in 1975, giving the equation:

$$T = 85.5\ V^{-.364} \qquad \text{(Eq. 8-2)}$$

Water depths less than 40 cm. were not used in the calculation because of the drag effects of the ice. The scatter diagram for this data is given in Figure 8-4. THe curvilinear correlation coefficient for the data in Figure 8-4 is -0.532. With 20 degrees of freedom, this inverse relationship is significant at the 1% level ($p > .99$).

During the winter of 1975-76, the mechanics of the thickening process were observed at the Orcutt ranch section. Three cross sections were established and small metal pylons were driven into the streambed to mark measurement locations. Current meter measurements were made at each location whenever the thickness was measured. Each location was measured seven times, and the growth of the ice sheet across each transect was monitored from time of first ice cover until the sheet began to break up. The results of the monitoring program are given in graphical form in Appendix G. It can be clearly seen from the diagrams, that during the early stages of surface ice formation, the thickness of the ice sheet is nearly uniform. Only areas of high velocity water remained open. As the thickening process continued, the rate of thickening was faster in areas of low velocity than in areas of high velocity. For any given temperature regime, each location showed a cessation of thickening after an initial period of growth. An insurgence of colder temperature caused a resumption

Figure 8-1: Cross sectional diagram of surface ice sheet at SH Ranch section, 2/13/75. Vertical exaggeration 12.5 X. Ice sheet represented by cross-hatched area.

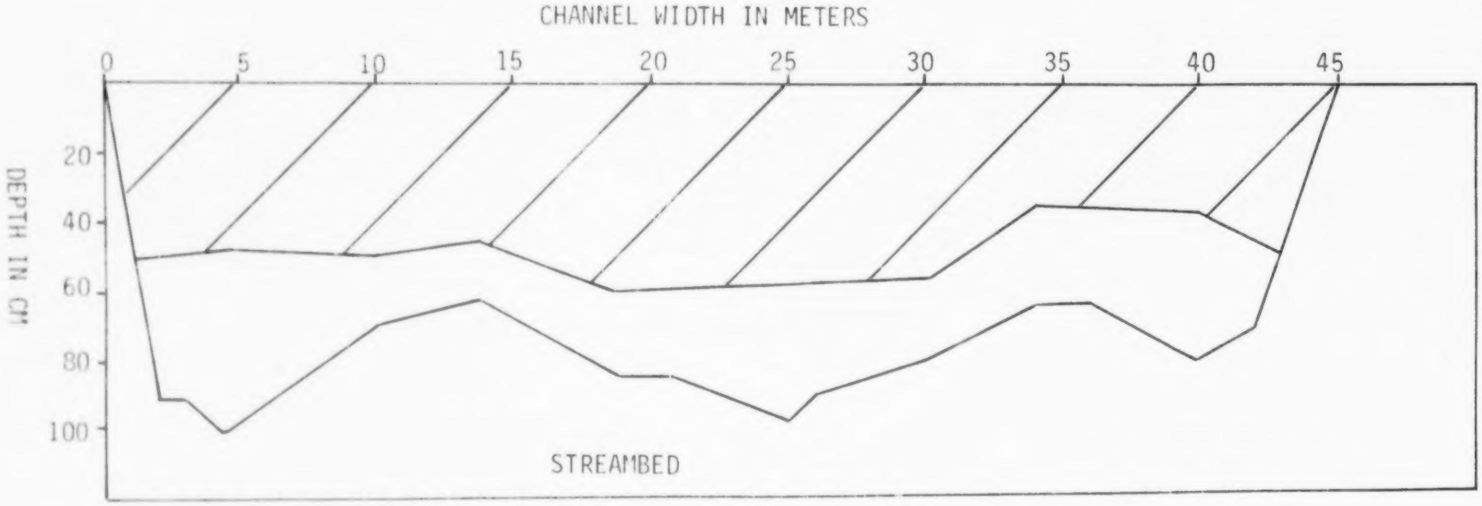


Figure 8-2: Cross sectional diagram of surface ice sheet at Viall Ranch section, 2/20/75. Vertical exaggeration 12.5 X. Ice sheet represented by cross-hatched area.

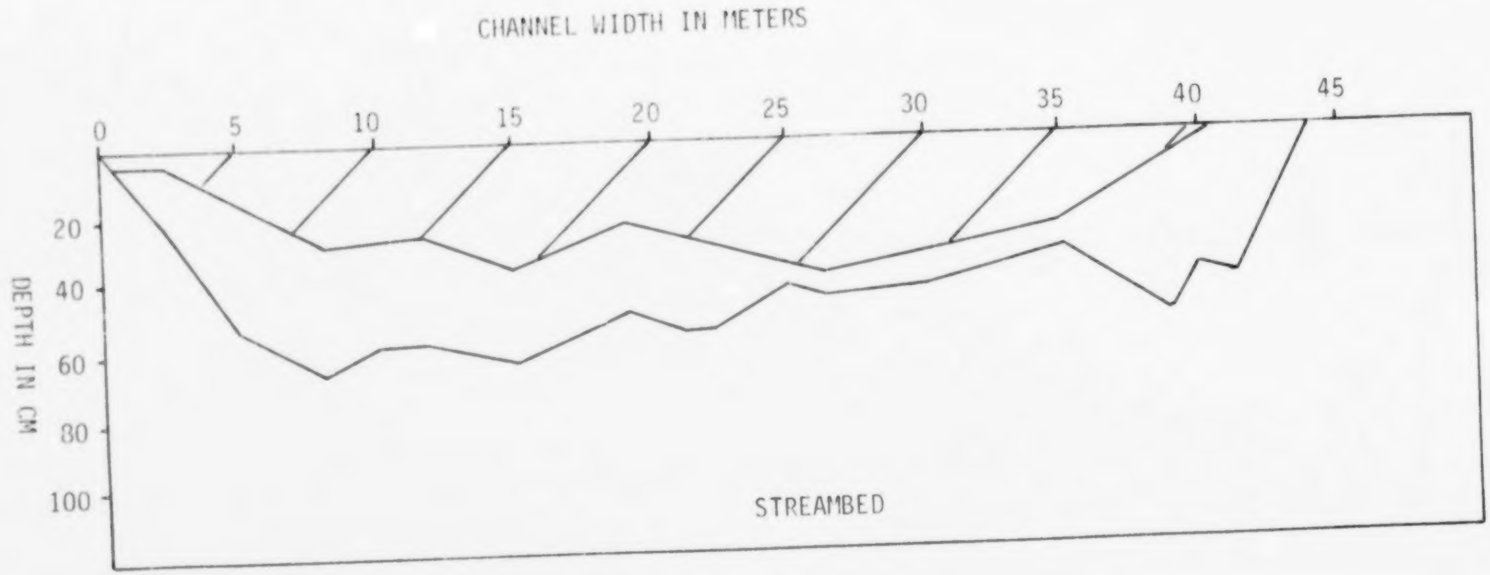
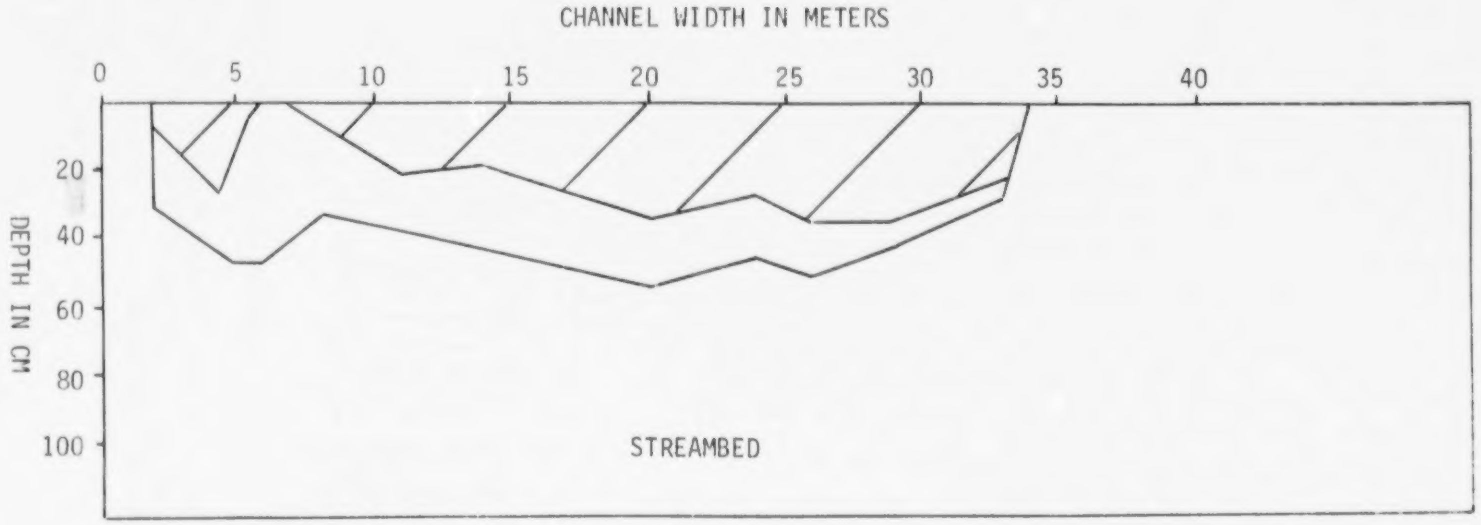


Figure 8-3: Cross sectional diagram of surfa-e ice sheet at Birney section, 2/26/75. Vertical exaggeration 12.5 X. Ice sheet represented by cross-hatched area.



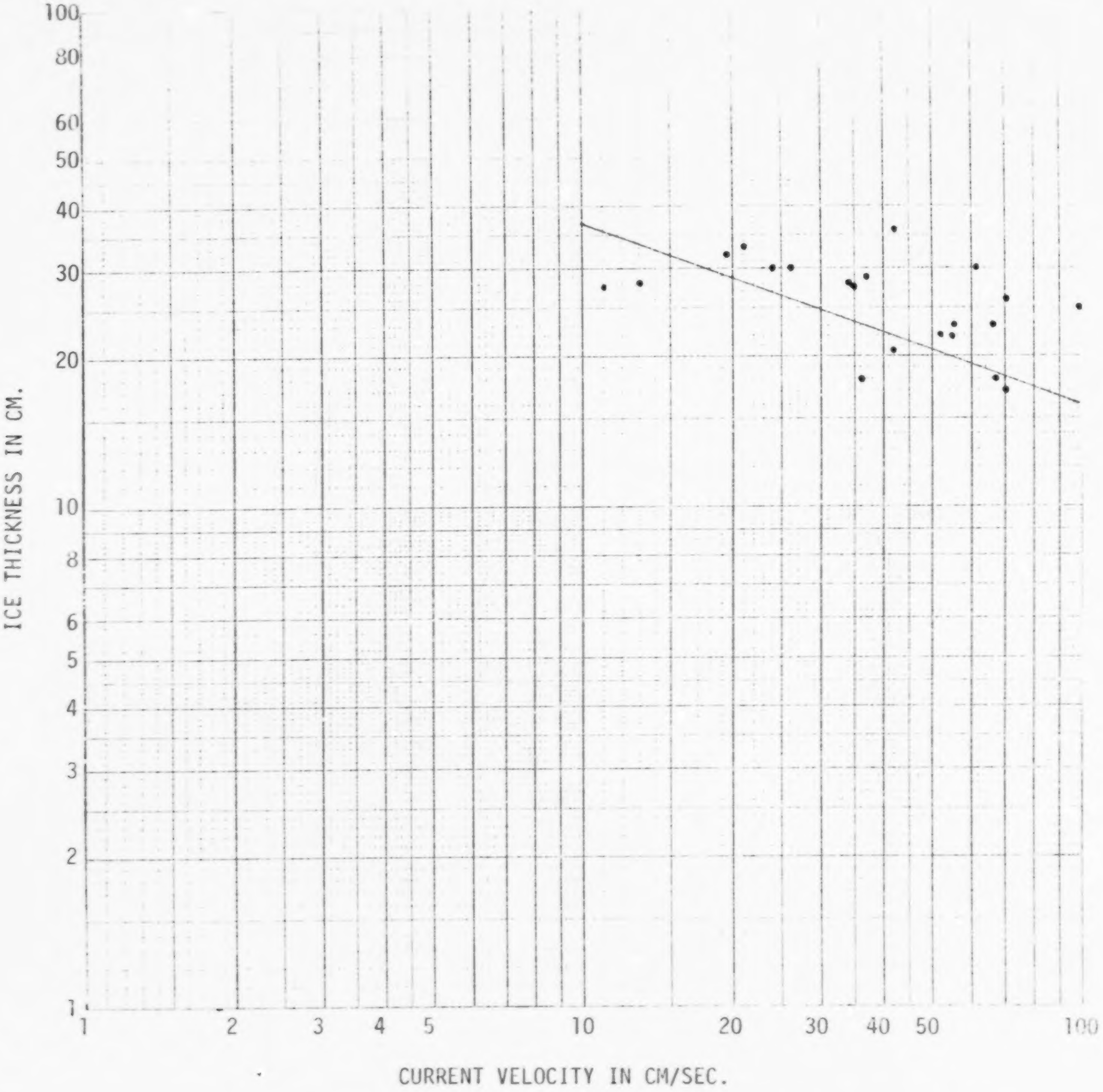


Figure 8-4: Relationship between current velocity and ice thickness in the Tongue River during the winter of 1974-1975. Data points are for water areas greater than 40 cm. in depth.

in growth at each location, until a new equilibrium thickness was attained.

Paily, et. al. (1975) have described the dependence of the melting rate of an ice cover on the flow parameters beneath it, and the temperature of the air over it. The non-dimensional differential equation describing the rate of thickening is given in Equation 8-3.

$$\frac{dS}{d\tau} = \frac{1 - HT\ (1 + S)}{1 + S}\ ; \quad S_{(\tau = 0)} = \frac{h_{wi}}{k_i}\ S_0 \qquad \text{(Eq. 8-3)}$$

Where $S = (h_{wi}/k_i)\ s$; $\tau = t/p_i L_i k_i/h_{ia}^2(T_m - T_a)$; $T = (T_w - T_m)/(T_m - T_a)$; $H = h_{wi}/h_{ia}$; $T_m = 0\ ^{\circ}C$, is the temperature at the water-ice interface; T_a is the air temperature; T_w is the average water temperature; h_{ia} is the coefficient of heat transfer from ice to air; h_{wi} is the coefficient of heat transfer for, water to ice; s is the thickness of the ice; k_i is the thermal conductivity of ice; p_i is the density of ice; L_i is the latent heat of fusion; and t is time. The criterion for equilibrium thickness ($dS/d\tau = 0$) is obtained from the following:

$$S_e = \frac{1}{H\ T} - 1 \qquad \text{(Eq. 8-4)}$$

Where,

S_e = equilibrium thickness.

H = ratio between heat transfer rates from water to ice and ice to air.

T = the ratio between the temperature of the water and air, respectively.

Equation 8-4 shows that for HT greater than or equal to one, the equilibrium thickness is zero. Only for HT less than one, will melting lead to stabilization of the ice cover after finite time. In fact, melting is perhaps the wrong expression to describe the equilibrium condition.

Examination of the parameters included in Equation 8-4 can give some insight into the mechanism by which ice forms at different rates across a river section. H is the ratio between the heat transfer rates from water to ice, and from ice to air, respectively. In an unheated stream (no source of thermal effluent) the major source of heat must be frictional heat, produced by running water, along the bed and the ice interface. Higher rates of heat production may be expected where the water velocity is faster. This will tend to give H a higher value and, therefore, require a smaller value of T (a colder ambient air temperature) to offset the effect of the higher value of H. This hypothesis may explain the variation in thickness with respect to current velocity.

Use of equation 8-4 will be limited until values for h_{wi} can be determined. Paily, et. al. (1974) have given several determinations of h_{ia}, and have shown that the base exchange rate is primarily a function of air temperature and wind velocity. The value of h_{wi} is most likely a function of water temperature, water velocity, bed roughness, and perhaps ice thickness (resulting in an increased normal force). At this time, values of h_{wi} are not available, but it may be possible to estimate heat production from running water through the use of the Bernoulli equation.

$$E_N = Z_N + D_N + \frac{V_N^2}{2g} \qquad \text{(Eq. 8-5)}$$

Where,

E_N = total energy at location N

Z_N = bed elevation at location N

D_N = depth at location N

V_N = velocity at location N

Potential heat production may be represented as the difference in total energy between two locations in the stream, as in Equation 8-6.

$$h_{wi} = \quad E = E_1 - E_2 \qquad \text{(Eq. 8-6)}$$

Biological Effects of Ice Formation

Little information is available concerning the effects of ice on the aquatic ecosystem, although certain relationships can be hypothesized. Formation of surface ice will have its greatest impact on organisms, particularly aquatic insects, living in shallow water areas. The most obvious effect of ice formation will be the loss of habitable area where the ice sheet extends down to the streambed. Because of the large drag effect of the ice where the water envelope (the open water area between bed and ice interface) is small, many areas not frozen to the bottom may have insufficient velocities to support the more velocity limited species.

Another important effect is demonstrated in the material of Appendix I. As the ice column builds toward the streambed, there is a steady decline in velocity and conveyance area in some parts of the channel. Since the discharge is not appreciably affected by freeze-up, the same discharge must be conveyed through a significantly reduced channel area. This results in water being diverted into the thalweg areas, frequently with an increase in velocity. This velocity increase may convert thalweg areas to suitable habitat for velocity-oriented organisms; it is also possible that the velocities may exceed the preferences or tolerances of many invertebrates.

The most spectacular phenomenon associated with surface sheet ice in rivers is that period during early spring when the ice pack breaks-up. As liquid water forms on the surface of the ice sheet, it carries heat into the cracks in the ice. The once solid mass of ice is transformed into a honeycomb structure of long crystals oriented normal to the surface, a structure which, while occupying the same volume as solid ice, is mechanically much weaker (Parsons, 1940).

Eventually, the more weakly-bound blocks of ice break loose from the mass and begin floating downstream. Where a controlling feature in the channel is encountered, such as a shallow area, constriction, or block of ice still frozen to the bed, the floating ice pack begins to pile up. This tends to dam water behind the jam, aiding in the release of more ice blocks from up-stream areas. These new ice blocks then stack up behind, and on top, of the original jam. The process may be repeated several times before a sufficient head is developed to release the entire ice jam. When release finally does occur, huge blocks of ice are tumbled through the water, grinding into the bed and banks of the river.

It is almost inconceivable that ice break-up would not have an effect on the river ecosystem. It would seem that the aquatic invertebrates, in particular, would suffer most from this phenomenon, although fish might be affected. However, so little is known of the over-wintering habits of fish and invertebrates in rivers, that is is difficult to even speculate what the effects of break-up would be on a river system.

A more quantifiable effect of ice movement is the structural damage done by ice to pumping stations, bridges, and head gates along the river. Each year several of these kinds of structures are damaged by the formation and release of jams. Plate 8-1 shows a pumping station on the Tongue River that was nearly destroyed by the ice break-up during the spring of 1975.

Water Requirements to Minimize Ice Problems

If water levels in the Tongue River are reasonably high during the formation and growth of the surface ice sheet, the ice will probably not cause an appreciable problem. The extent to which the controls will be frozen from top to bed may be assessed empirically through the use of Figure 8-4, and the hydrologic maps of Appendix A.

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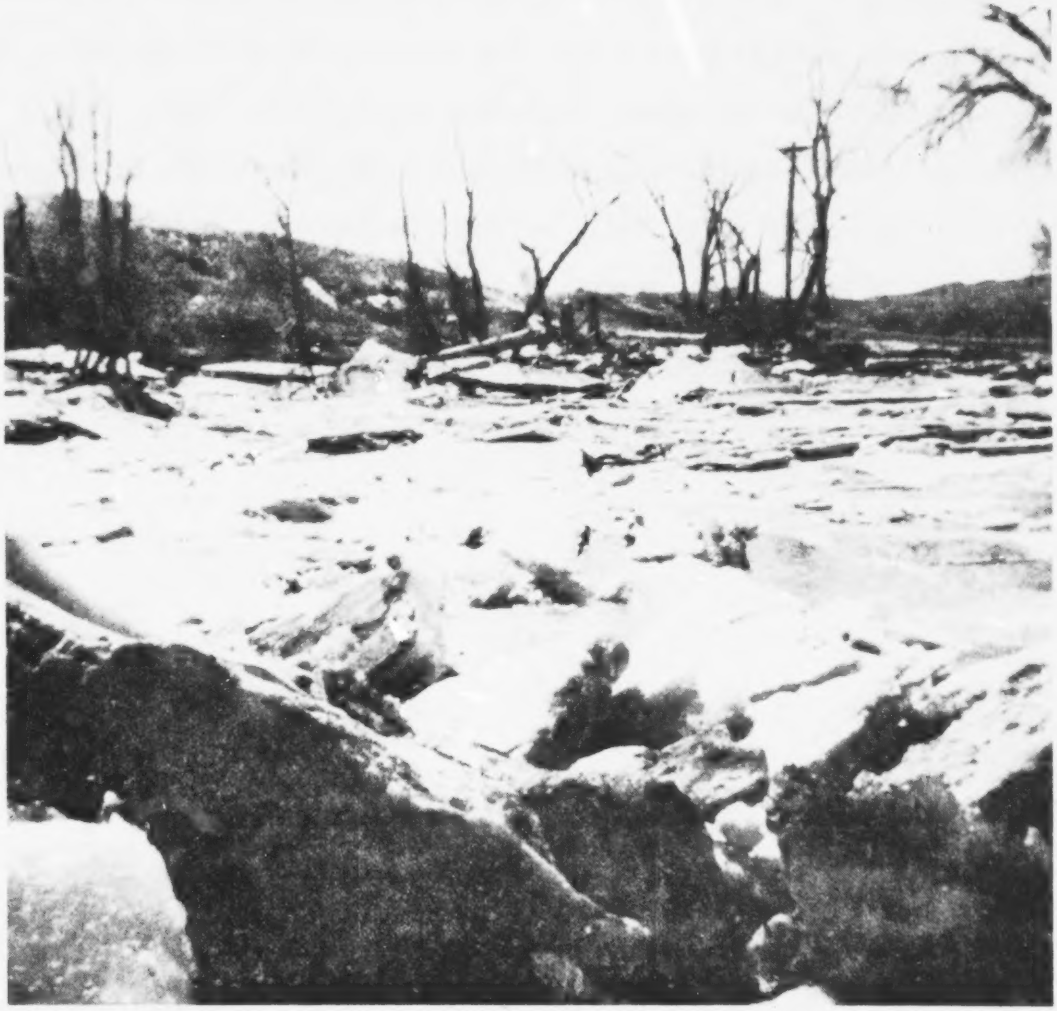

Plate 8-1: Pumping station (far bank) at the SH Ranch which was nearly destroyed by ice jamming in February, 1975. The elevation of the pump is about 6 meters above the streambed. This jam extended upstream for several kilometers.

For areas included within the 60 cm./sec. velocity contours, the ice thickness should be about 20 cm. For areas within the 45 cm./sec. coutours, the thickness would be around 22 cm; and within the 30 cm./sec. contour, the thickness would be about 25 cm. The flotation depth for the ice is defined as 90% of the thickness. It is then possible to estimate, from the depth and velocity contour maps of Appendix A, the approximate percentage of the control which would likely be frozen to the bed. Table 8-1 shows the extent of freezing for several discharges at the Viall section.

Table 8-1: Approximate percentage of channel area frozen from surface to streambed at various discharges at the Viall Ranch section during a winter of normal severity.

Discharge (cms.)	Percent Streambed Frozen (Approximate)
6.30	5 - 10%
5.58	20 - 30%
4.02	50 - 60%
2.38	75 - 80% **

** with a potential loss of circulation

The hydrologic maps of Appendix A may also be used to estimate the discharge required to minimize ice jams during break-up. Assuming that ice blocks during break-up will average 30 cm. in thickness, areas less than 30 cm. in depth will be prone to collect ice. Since the ice in the lower river tends to be thicker than in the upper river, larger passage requirements would have to be met. However, at the Viall section, ice jams would form across at least half the channel at any flow less than 5.58 cms. Jams covering one-third of the channel might be expected at flows of 10.2 cms;

and one-fourth the channel at 12.0 cms. Flows of 19.4 cms. would probably be free of ice jams, but flows of less than 4.0 cms. may result in total jamming of the channel. Total jamming would most certainly be expected at a flow of 2.83 cms.

While it may not be possible to maintain a flow of 20.0 cms. for the purpose of flushing ice from the river system, it may be desirable to maintain a flow of from 10.0 to 12.0 cms. to control the extent of ice jamming. Maintenance of flows near or below the base flow level can be expected to result in extensive and potentially damaging ice jams.

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CHAPTER 9: CONSUMPTIVE USE BY RIPARIAN VEGETATION

Introduction

The relationship between a river and the riparian community existing on its floodplain might be described as symbiotic. The dependence of the vegetation on the river as the primary water source is paramount. However, the river ecosystem also receives major benefits from the riparian community.

Perhaps the most obvious benefit is the shade and cover provided by overhanging vegetation. Water temperatures may be moderated considerably due to the shading effect. Bowie and Kam (1968) noted that water temperatures along a 2.4 km. defoliated reach of a small stream increased 4° to 6° F. during the summer and were 7° to 8° F. colder during the winter, compared to an upstream control section.

Fish benefit directly from the cover provided by vegetation. In addition to the cover afforded by dead snags and log jams, riparian vegetation is the single most important factor in the formation of undercut banks. Alluvial channels tend to have unstable banks, and the existence of these favored hiding places is attributable almost totally to the stabilization of the banks by vegetation.

The riparian community also makes a significant contribution to stream energetics. Hynes (1972) and others have noted that leaves and other debris which fall into the water are often heavily utilized by stream herbivores. Chapman (1966) estimated that 51% of the aquatic portion of the coho salmon diet, in a small stream he studied, originated from allochthonous sources.

Riparian vegetation may also play an important role in maintaining good water quality. In the process of removing water from the river, trees and brush also remove the salts and nutrients dissolved in the water. Because these plants are generally long-living and slow to decompose, there can be a considerable storage of these materials. Compared to the rapid decompostion and nutrient release characteristic of many species of algae, salt removal by riparian vegetation may indeed be considered long-term storage.

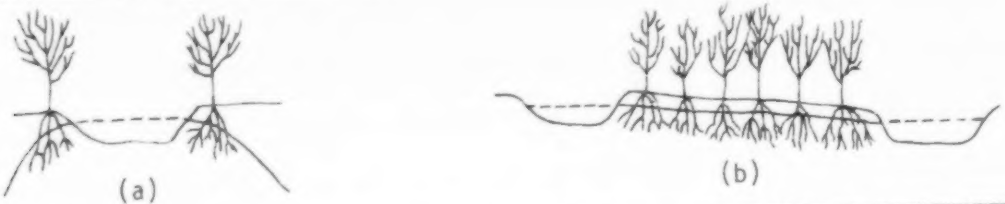
Groundwater Supply Mechanisms

In the discussion of water requirements for riparian vegetation, it is important to determine the mechanism by which the plants are supplied with water. Along many of the small ephemeral streams in the Northern Great Plains, the vegetation must rely on bank storage. By this mechanism, a large spring runoff is required to recharge the local groundwater zone with a sufficient water supply to support the vegetation through the growing season. This supply is periodically augmented by precipitation. Also, the vegetation tends to conserve available moisture by lowering its evapotranspiration rate when supplies are low (Robinson, 1956).

Riparian vegetation along the Tongue River is apparently supplied with water on a continuous basis. This situation is suggested by the nature of the floodplain materials, and by the patterns of vegetation along the river. Core samples were taken at several locations along the Tongue River floodplain, and each sample indicated that the floodplain was composed primarily of coarse gravel. There was usually so little clay present in the matrix that the walls of the hole invariably caved in before casings could be installed. By virtue of this low clay content, it is unlikely that the Tongue River floodplain has the storage capability to support the vegetation community in existence over even short periods of time without a continuous source of water. However, the transmissivity of the floodplain is likely to be extremely high.

This "flow through" mechanism is also suggested by the pattern of vegetational development in response to channel sinuosity. It can be seen from the maps in Appendix J that areas with short wavelength and tortuous meanders generally have more vegetation than long meanders or straight sections. In these accentuated areas the groundwater flow probably moves directly across the meander loop. Figure 9-1 illustrates the difference that channel sinuosity can make in establishing the depth to groundwater.

Figure 9-1: Hydraulic gradient of floodplain groundwater in straight (a) and meandering (b) channels.



It is highly significant that the bulk of the vegetation on the Tongue River floodplain obtains its water in a continuous manner similar to illustration (b) in Figure 9-1. Because the depth to groundwater is never very great, the head resistance to the osmotic pressures causing evapotranspiration is minimized. Therefore, the vegetation may use water at higher rates than if the depth to water were greater.

Evapotranspiration of river water must be considered an unavoidable loss, and as such, becomes a distinct in-stream flow requirement. If the flow requirements for evapotranspiration are not considered, the rearing flow for the fisheries may be seriously depleted.

Riparian Evapotranspiration on the Tongue River

Methodology:

The estimation of the daily and instantaneous water volume requirements for evapotranspiration involved two separate operations: 1) the estimation of the total canopy cover of the floodplain, and 2) the estimation of the potential evapotranspiration rates from climatological data.

Color aerial photos of the Tongue River were used to determine areas of vegetation cover. Vegetated areas were outlined on ruled tracing paper with the use of a light-table. These areas were delineated so that each small square of the grid system was occupied by at least one tree. Areas of similar canopy density were identified and given a weighting factor based upon the approximate percentage of each square covered by vegetation. Plates 9-1 and 9-2 illustrate one such aerial photo and corresponding vegetation map. Appendix J contains the vegetation maps for the Tongue River from the T & Y Diversion dam to several kilometers above Ashland, Montana.

Vegetated areas were then measured by polar planimeter and tabulated according to percent-cover class. Data compilation for each map entailed: calculation of the total weighted canopy cover; measurement of river length in km.; and calculation of average canopy cover per km. of river. Table 9-1 gives the total canopy cover and canopy cover per km. of river length for each vegetation map. This data is also cross-referenced to Appendix J. The average canopy cover for the 160 km. of river measured was 6.5 hectares per km. This is equivalent to about 26 acres per mile. The total length of the Tongue River is 303 km. from the Tongue River Dam to the mouth. Assuming that the area measured is representative of the entire river, the total area of canopy is 1970 hectares, or 19,700,000 square meters.

The rate of potential evapotranspiration was calculated using a variation of the Penman equation (Criddle, 1958). (See also: Penman, 1956; Tanner and Pelton, 1960; Van Bavel, 1966). There are several variations of Penman's original model, each requiring climatological measurements of varying sophistication. The variation suggested by Criddle (1958) was selected because its data requirements were more accessible than the more sophisticated models of Van Bavel (1966) or Tanner and Pelton (1960).

The Penman equation is an energy balance method in which several assumptions are made. The first assumption is that the total energy received by the earth's surface through radiation must equal the sum of 1) the energy used for evaporation, 2) heating the air, 3) heating the soil and 4) any

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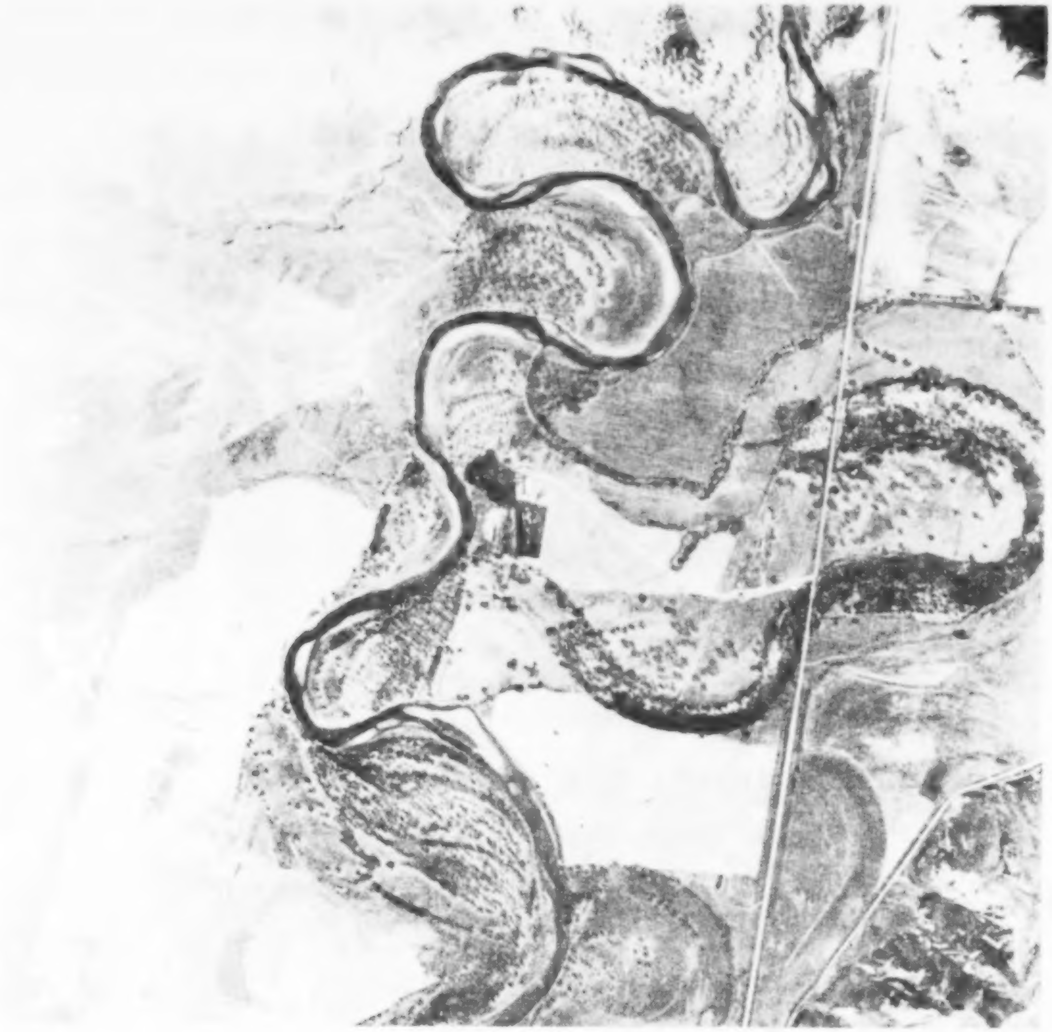

Plate 9-1: Aerial photograph showing canopy cover of the riparian vegetation of the Tongue River floodplain, in the vicinity of Ash Creek. Photo courtesy of the Montana Department of Fish and Game.

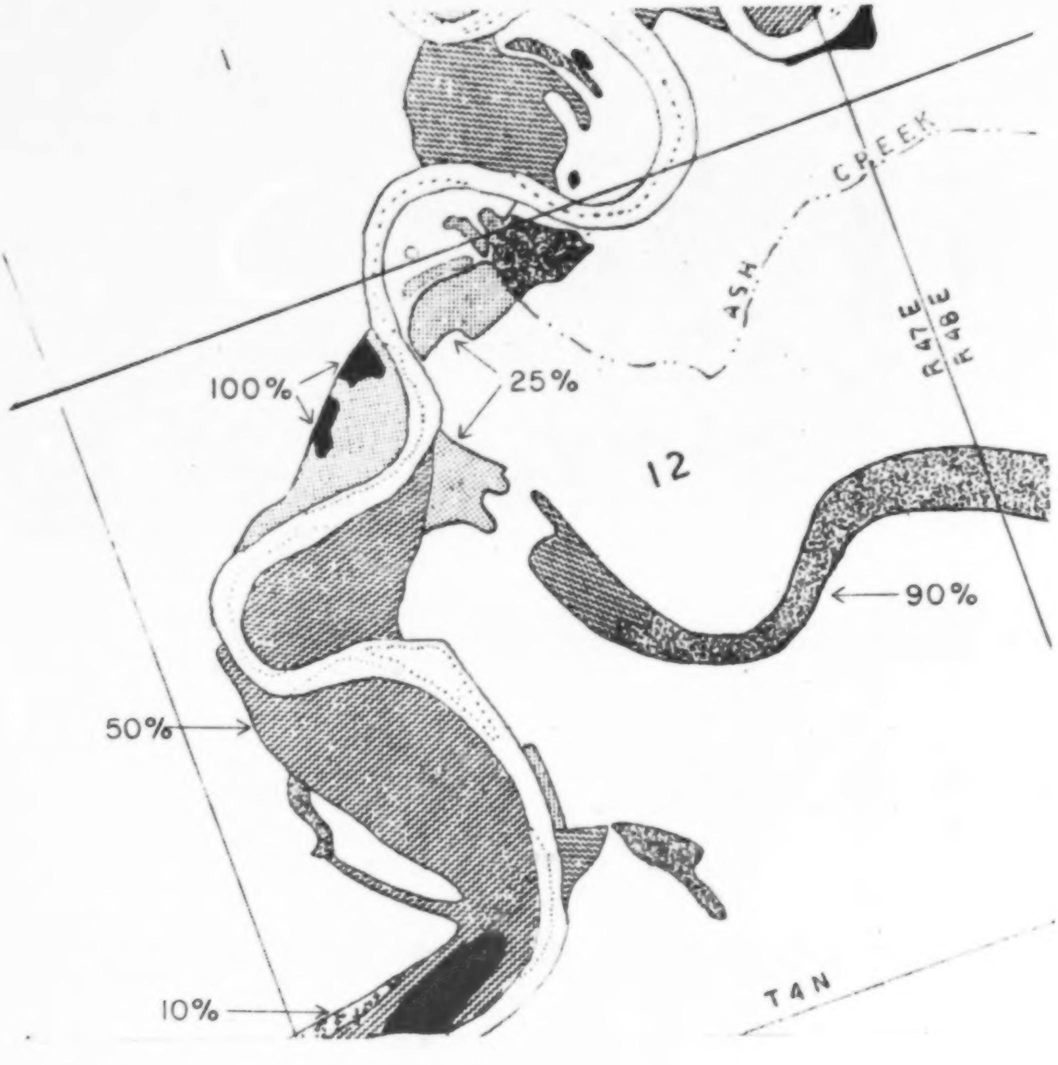

Plate 9-2: Vegetation map showing canopy cover density as estimated from the aerial photo (Plate 9-1) of the Tongue River floodplain near Ash Creek.

Table 9-1: Total Canopy Cover and Canopy Cover per km. for the Tongue River from T & Y Diversion to above Ashland, Montana.

Plate Number (App. J)	River Length km.	Total Canopy Cover			Canopy Cover per Km.		
		Willow Ash hectares	Cottonwood hectares	Total hectares	Willow Ash ha/km	Cottonwood ha/km	Total ha/km
J - 1	3.87	6.8	18.5	25.3	1.8	4.8	4.8
J - 2	3.17	0.7	4.4	5.1	0.2	1.4	1.4
J - 3	5.12	1.5	31.7	33.2	0.3	6.2	6.2
J - 4	3.26	0.0	9.2	9.2	0.0	2.8	2.5
J - 5	3.23	4.0	8.1	12.1	1.2	2.5	2.8
J - 6	5.25	5.1	14.9	20.0	1.0	2.8	8.0
J - 7	4.51	6.9	36.1	43.0	1.5	8.0	1.6
J - 8	2.59	3.7	4.1	7.8	1.4	1.6	3.8
J - 9	4.91	4.9	18.6	23.5	1.0	3.8	5.6
J - 10	3.75	8.1	21.0	29.1	2.2	5.6	
J - 11	4.54	1.9	21.9	23.8	0.4	4.8	4.8
J - 12	4.82	21.4	20.4	41.8	4.4	4.2	4.2
J - 13	3.48	4.8	13.7	18.5	1.4	3.9	3.9
J - 14	3.17	7.3	8.1	15.4	2.3	2.6	2.6
- 15	3.72	3.8	10.1	13.9	1.0	2.7	2.7
J - 16	3.23	3.9	12.8	16.7	1.2	4.0	4.0
J - 17	3.17	7.4	7.2	14.6	2.3	2.3	2.3
J - 18	3.90	7.3	12.2	19.5	1.9	3.1	3.1
J - 19	4.38	8.6	6.6	15.2	2.0	1.5	1.5
J - 20	3.60	8.6	4.1	12.7	2.4	1.1	1.1
J - 21	3.22	3.3	8.0	11.3	1.0	2.5	2.5
J - 22	5.00	10.9	18.0	28.9	2.2	3.6	3.6
J - 23	4.12	15.2	36.4	51.6	3.7	8.8	8.8
J - 24	5.76	38.1	22.2	60.3	6.6	3.9	3.9
J - 25	4.72	27.5	37.6	65.1	5.8	8.0	8.0

Table 9-1: Total Canopy Cover and Canopy Cover per Km. for the Tongue River from T & Y Diversion to above Ashland, Montana.

Plate Number (App. J)	River Length km.	Total Canopy Cover			Canopy Cover per Km.		
		Willow Ash hectares	Cottonwood hectares	Total hectares	Willow Ash ha/km	Cottonwood ha/km	Total ha/km
J - 26	5.15	24.1	29.0	53.1	4.7	5.6	10.3
J - 27	3.66	20.7	32.5	53.2	5.7	8.9	14.5
J - 28	4.15	13.2	21.7	34.5	3.2	5.2	8.4
J - 29	3.71	11.9	20.6	32.5	3.2	5.6	8.8
J - 30	3.14	2.1	6.6	8.7	0.7	2.1	2.8
J - 31	3.97	1.7	16.9	18.6	0.4	4.3	4.7
J - 32	2.41	0.5	10.0	10.5	0.2	4.1	4.4
J - 33	1.94	1.9	8.5	10.4	1.0	4.4	5.4
J - 34	3.75	6.9	33.4	40.3	1.8	8.9	10.7
J - 35	3.90	7.8	17.9	25.7	2.0	4.6	8.6
J - 36	4.77	12.5	24.2	36.7	2.6	5.1	7.7
J - 37	5.98	16.6	23.6	40.2	2.8	3.9	6.7
J - 38	6.47	12.6	32.3	44.9	1.9	5.0	6.9
J - 39	3.74	17.1	16.0	33.1	4.6	4.3	8.9
J - 40	3.43	11.6	15.2	26.8	3.4	4.4	7.8
TOTAL	160.66	372.9	714.3	1087.2	87.4	172.9	260.3
AVERAGE	NA	9.3	17.9	27.2	2.2	4.3	6.5

extraneous or advected energy. It is further assumed that for short periods, such as daily and monthly balances, the latter two items may be neglected without seriously affecting the accuracy of the method. Tanner and Pelton (1960) state that the soil heat flux is least during the summer months when the soil temperature is near maximum. The greatest soil flux errors occur during the spring and fall when soil temperatures change rapidly. This assumption is considered valid on the grounds that the soil heat flux is most stable during the important growing season months.

The application of this model also requires the estimation or measurement of the net radiation received by the surface, and partitioning this energy between heating of the air and evaporation of water. Distribution is assumed to occur according to the Bowen ratio, a fraction dependant upon the temperature and water vapor pressure at the surface, and at some height above the surface. If the Bowen ratio is approximated from mean daily data, an error will result from the strong weight given night-time values when there is little evapotranspiration (Tanner and Pelton, 1960). Since mean daily temperatures were used to determine the mean daily evapotranspiration rates, this error will cause under-estimation of these rates.

It was further assumed that monthly weather conditions as measured at the Miles City FAA airport are representative of the conditions for the length of the river. In most data this assumption is valid, with the possible exception of wind velocities. Location of the airport, on a high plateau, insures that wind velocities will be somewhat higher than they are in the valley. However, it can be demonstrated that a 25% overestimation of the wind velocity results in an error of only about 8% in the potential evapotranspiration rate.

The Penman equation as presented by Criddle (1958) uses the following three formulas:

$$H = R_a\ (1 - r)(.18 + .55n/N) - \sigma T_a^4\ (.56 - .092\sqrt{e_d})(.1 + .9n/N) \quad \text{(Eq. 8-1)}$$

$$E_a = .35\ (e_a - e_d)(1 + .0098\ u_2) \quad \text{(Eq. 8-2)}$$

$$E_t = \frac{\Delta H - .27\ E_a}{\Delta - .27} \quad \text{(Eq. 8-3)}$$

Where,

H = Daily heat budget at surface in mm. H_2O/day

R_a = Mean monthly solar radiation in mm. H_2O/day

r = Reflection coefficient of surface = .19*

n/N = Ratio of actual duration of bright sunshine to the maximum possible duration, mean monthly

σ = Boltzman constant = 2.01×10^{-9} mm/day

T_a = Terrestrial, or Back radiation in mm. H_2O/day

e_a = Saturation vapor pressure at mean air temperature in mm. Hg.

e_d = Actual vapor pressure (e_a x relative humidity)

E_a = Evaporation in mm. H_2O/day

u_2 = Mean wind velocity at 2 meters above ground in miles per day.

E_t = Potential evapotranspiration in mm. H_2O/day

Δ = First Derivative of saturation vapor pressure-temperature curve, dVP_s/dT

*From Aase, Wight, and Siddoway (1973).

Two sources of data were used in computing the Penman model. Daytime means of temperature, relative humidity, percent sunshine, and wind velocity were obtained from Climatological Data for Montana, National Oceanic and Atmospheric Administration, 1972. These values were used to compute the mean daily evapotranspiration rate. Average noon values for temperature and relative humidity were used to estimate mean daily maximum rates. Other inputs for the model were obtained from charts and tables provided by Criddle (1958). Climatic data and model inputs are listed in Tables 9-2 and 9-3 respectively.

Computation of Evapotranspiration Rates and Correction for Precipitation:

While most of the water used by the riparian community comes directly from the river, a portion of each month's total requirement is satisfied by meteoric water. Therefore, a correction for rainfall is made in the mean monthly evapotranspiration rate as found in Table 9-4. The term "effective precipitation" is used in Table 9-4 to describe the total amount of monthly precipitation of sufficient intensity to influence the ground water supply. It is generally accepted that storms with intensities of less than 2.5 mm. per day of precipitation do not effectively change the soil moisture (Aase, et.al., 1973). In addition, it was assumed that approximately 10% of the measureable precipitation is intercepted by the vegetation and is directly evaporated. Actual interception will range from 100% for light showers to less than 10% for heavy rains. Effective precipitation was calculated according to the expression:

$$EP = .9\,(P - p) \qquad \text{(Eq. 9-4)}$$

Where:

EP = Effective precipitation in mm./month

P = Mean monthly total precipitation in mm./month

p = Mean monthly precipitation from storms delivering 2.5 mm/day or less, in mm./month.

The average monthly effective precipitation was subtracted from the monthly potential evapotranspiration rate to determine the monthly "evapotranspiration deficit." This term represents the approximate amount of water supplied by the river for evapotranspiration during months of normal

Table 9-2: Climatological data for Miles City, Montana. Period of record = 39 years. From: "Climatological Data for Montana", National Oceanic and Atmospheric Administration, 1972.

Month	Temperature mean daily	Temperature mean noon	Relative Humidity mean daily	Relative Humidity mean noon	Sunshine mean day	Wind Speed mean day
	°C	°C	%	%	%	miles/day
April	8.3	14.4	59	45	60	278
May	13.3	20.0	56	41	61	264
June	18.9	25.6	57	44	66	242
July	23.3	30.6	50	37	76	228
August	22.2	30.0	50	38	78	228
September	15.6	22.8	57	43	64	235

Table 9-3: Inputs to Penman equation, derived using climatic data from Table 9-2. From: Criddle, W.D., 1958, "Methods of Computing Consumptive Use of Water," Irrigation and Drainage Division, Paper 1507: (Proc. Am. Soc. Civil Eng.) 1-27.

Month	Radiation Intensity mm H_2O/day	Vapor Pressure Saturation mm Hg	Vapor Pressure Actual mm Hg	σT_a^4 mm H_2O/day	Δ
April					
mean daily	13.30	8.20	4.84	12.65	.31
mean noon		12.30	5.54	13.76	.45
May					
mean daily	15.65	11.45	6.41	13.55	.42
mean noon		17.53	7.19	14.87	.60
June					
mean daily	16.70	16.37	9.33	14.64	.57
mean noon		24.62	10.83	16.01	.80
July					
mean daily	16.20	21.46	10.73	15.54	.71
mean noon		32.94	12.19	17.09	1.04
August					
mean daily	14.35	20.07	10.04	15.32	.67
mean noon		31.83	12.10	16.97	1.00
September					
mean daily	11.35	13.29	7.58	13.96	.48
mean noon		20.82	8.95	15.43	.70

rainfall. Values for mean monthly evapotranspiration, effective precipitation, and evapotranspiration deficit are found in Table 9-4. Table 9-5 gives the mean daily evapotranspiration rate, the rainfall-corrected mean daily rate, and the mean daily maximum rate. The latter term was incorporated to determine the potential instantaneous flow requirement during the peak water use period of each day. Van Bavel (1966) shows that there is a large peak in the rate of evapotranspiration between 11:00 a.m. and 3:00 p.m., corresponding to the period of maximum temperature, radiation intensity, and vapor pressure deficit.

The instantaneous flow requirements were determined for each calculated evapotranspiration rate by converting the rate to meters per day and multiplying by the total area of canopy cover. This gives the potential rate of daily consumption in cubic meters per day. Dividing the total volume per day by 86,400 seconds per day gives the average instantaneous flow in cubic meters per second. These values are listed in Table 9-6 for the three different rates of evapotranspiration. It was assumed that inflow to the ground water regime was constant over the 24-hour period; therefore, the values in Table 9-6 should be considered conservative. If it had been assumed that ground water inflow accelerated during the daylight period, these figures would approximately double.

Irrigation: A Special Case of Evapotranspiration

Irrigation may be defined as the use of water to supply any deficit between precipitation and potential evapotranspiration. This definition implies that the rate of evapotranspiration is not limited by the availability of soil moisture. Therefore, irrigated crops may be considered a special classification of riparian vegetation.

According to U.S. Geological Survey streamflow records, approximately 10,200 hectares of cropland are irrigated with water from the Tongue River

Table 9-4: Effective precipitation, evapotranspiration, and net evapotranspiration deficit; based on local climatological data and the Penman equation.

Month	Effective Precipitation mean monthly mm/month	Potential Evapotranspiration mean monthly mm/month	Evapotranspiration Deficit mean monthly mm/month
April	16.6	102.6	86.0
May	43.0	141.0	98.0
June	56.5	172.0	118.5
July	33.0	202.5	169.5
August	20.6	179.0	158.4
September	19.4	110.0	90.6

Table 9-5: Mean daily evapotranspiration, corrected mean daily evapotranspiration, and mean daily maximum evapotranspiration rates.

Month	Mean Daily Evapotranspiration mm/day	Mean Daily Evapotranspiration Deficit* mm/day	Mean Daily Maximum Evapotranspiration mm/day
April	3.42	2.86	4.85
May	4.70	3.26	6.45
June	5.74	3.96	7.46
July	6.75	5.65	8.53
August	5.96	5.28	7.75
September	3.66	3.02	5.20

* Evapotranspiration Deficit refers to the mean daily E_t rate, corrected for rainfall.

Table 9-6: Mean daily, rainfall-corrected mean daily, and mean daily maximum instantaneous flow requirements for riparian vegetation on the Tongue River.

Month	Instantaneous Flow Requirement mean daily m^3/sec (cfs)	Instantaneous Flow Requirement Mean daily (rain corrected) m^3/sec (cfs)	Instantaneous Flow Requirement mean daily maximum m^3/sec (cfs)
April	0.78 (28)	0.65 (23)	1.10 (39)
May	1.07 (38)	0.74 (26)	1.48 (52)
June	1.31 (46)	0.90 (32)	1.69 (60)
July	1.54 (54)	1.29 (46)	1.94 (69)
August	1.36 (48)	1.20 (42)	1.76 (62)
September	0.83 (29)	0.69 (24)	1.18 (42)

between the Tongue River Dam and Miles City. Including the total area of trees along the river, the total area of "riparian vegetation" is 12,170 hectares. Irrigated crops occupy 89%, and true riparian vegetation 11% of the total area. Evapotranspiration from irrigated crops will be the primary consumptive use by vegetation of all types.

Several assumptions are made in the estimation of crop evapotranspiration; 1) The rate of evapotranspiration for irrigated crops with an adequate water supply is assumed to be the same as for trees. The Penman equation was originally designed for the estimation of evapotranspiration from short crops with complete ground cover. If there is an error in this assumption, it is probably an underestimation of the water used by the trees; 2) while it is probably true that more water is supplied by irrigation than is actually used by the plants, it is assumed that most of the excess returns to the river; and, 3) it is further assumed that water supplies and soil moisture are not limiting.

Mean daily and rainfall corrected mean daily evapotranspiration volumes were computed for the primary irrigation months, May through September. Average instantaneous flow requirements were calculated on a 24-hour basis for both types of evapotranspiration rates. These values are listed in Table 9-7 along with riparian and total evapotranspiration requirements.

The accuracy of the values listed in Table 9-7 was tested using a water budget for the Tongue River between the Tongue River Dam and Miles City. The water balance equation is:

$$\text{Outflow} = \text{Inflow} - \text{Storage}$$

$$Q_o + E_t + E_a = Q_i + P - S \qquad \text{(Eq. 9-5)}$$

Where:

Q_o = measured streamflow at Miles City, in m^3/month

E_t = calculated evapotranspiration volume for total vegetation

Table 9-7: Mean daily instantaneous flow requirements (columns A) and rainfall corrected mean daily instantaneous flow requirements (columns B) for irrigated crops, riparian, and total vegetation on the Tongue River.

Month	Irrigation Instantaneous Flow Requirement m^3/sec. (cfs)		Riparian Instantaneous Flow Requirement m^3/sec. (cfs)		Total Instantaneous Flow Requirement m^3/sec (cfs)	
	A	B	A	B	A	B
May	5.56 (196)	3.85 (136)	1.07 (38)	0.74 (26)	6.63 (234)	4.59 (162)
June	6.77 (239)	4.68 (165)	1.31 (46)	0.90 (32)	8.08 (285)	5.58 (192)
July	7.97 (282)	6.67 (236)	1.54 (54)	1.29 (46)	9.51 (336)	7.96 (282)
August	7.05 (249)	6.25 (221)	1.36 (48)	1.20 (42)	8.41 (297)	7.45 (263)
September	4.32 (153)	3.57 (126)	0.83 (29)	0.69 (24)	5.15 (182)	4.26 (150)

in m^3/month

E_a = evaporation in m^3/month

Q_i = measured streamflow at Tongue River Dam in m^3/month

P = effective precipitation in m^3/month

S = in-basin storage in m^3/month

Estimates of storage and actual evaporation proved impossible to obtain. Since both factors are directly related to the availability of surface water from precipitation, it was possible to eliminate them from consideration by selecting months which had little or no effective rainfall. Test results are given in Table 9-8. It can be seen that even a small amount of precipitation can seriously affect the accuracy of the water budget. In most cases, the monthly volume of outflow calculated for Miles City is greater than the amount measured at the U.S.G.S. gaging station. This reflects losses to direct evaporation and storage, and possibly an underestimation of the evapotranspiration rate. It should be noted however, that where the errors in Table 9-8 are positive (calculated outflow is less than measured outflow), the error is less than 10%.

Results and Discussion

Despite the generalized nature of the data inputs for the Penman equation, the rates of potential evapotranspiration in Table 9-5 appear reasonable for the Tongue River climatic region. The seasonal total for potential evapotranspiration, calculated from the mean daily rates is slightly over 1 meter per growing season. Moulder, et. al. (1960) used an inflow-outflow-storage method to determine the actual evapotranspiration of a similar riparian community on the Little Bighorn River. They calculated a seasonal evapotranspiration of about .92 meters. It may be assumed that where soil moisture is not limiting, the actual rate of evapotranspiration will be about 90% of the potential rate. Thus, the rates given in Table

Table 9-8: Water budget for lower Tongue River basin to test accuracy of calculated values of evapotranspiration.

Year	Month	Q_i m^3/mo. x 10^8	EP m^3/mo. x 10^8	E_t m^3/mo. x 10^8	Q_o cal. m^3/mo. x 10^8	Q_o meas. m^3/mo. x 10^8	Δ m^3/mo. x 10^8	Percent error
1964	7	.715	0.88	.246	1.349	.738	-.611	-83
	9	.336	0.00	.134	.202	.217	+.015	+ 7
1967	8	.386	0.02	.218	.191	.145	-.046	-32
1968	4	.329	0.08	.126	.383	.328	-.055	-17
1969	8	.290	0.02	.218	.095	.124	-.029	-23
	9	.272	0.00	.134	.138	.137	+.001	+ 1
1970	8	.299	0.00	.218	.081	.105	-.024	-23

9-5 are probably accurate to within 10% of the actual rates.

The instantaneous flow requirements shown in Table 9-6 may seem large, but they actually represent a small incremental loss. The rate of change in discharge attributable to natural riparian vegetation is only about .004 m^3/sec per km. (.24 c.f.s. per mile) for the rainfall corrected mean for July. The largest and most significant consumptive use of water is the irrigation of crops. The average incremental loss to irrigation would be about .022 m^3/sec per km. (1.25 c.f.s. per mile) during the same period.

Table 9-7 shows that the in-stream flow requirements for both irrigation and riparian vegetation are very high. The use of means in Table 9-7 may result in serious error in the estimation of day-to-day instream flow requirements over relatively short periods. While the extraction of water by riparian vegetation is fairly predictable, extraction by irrigators is not. For example, rain may result in a complete halt in irrigating, leaving a surplus of water in the river. A prolonged drought, on the other hand, might result in all irrigators removing water on the same day. Such a demand would most assuredly result in actual streamflows being much less than the predicted means.

Table 9-8 is primarily useful in demonstrating that the instantaneous streamflow requirements calculated in this chapter are reasonably accurate. By eliminating storage and surface evaporation terms from the water budget by selecting months when rainfall was minimal, it was possible to compare predicted and actual water losses. By using monthly averages it was possible to smooth the erratic daily water use curves. Table 9-8 shows conclusively that if there is any significant error in the volume water requirements for total vegetation, it is probably an error of underestimation. In the two cases of overestimated evapotranspiration the errors were less than 7%.

Table 9-8 also shows that it is unwise to overestimate the effectiveness of rainfall to supply water for evapotranspiation. The assumption that rainfall plays an important role in contributing to either streamflow or evapotranspiration seriously underestimates the amount of direct surface evaporation, and to a lesser degree, the amount of storage. This error becomes greater as the amount of precipitation increases. The direct result of underestimating storage and direct evaporation is an overestimation of the predicted outflow at the mouth of the basin.

The relationship between in-stream flows for fisheries, and in-stream flows for riparian vegetation and downstream irrigation uses, is complex and subtle. If all the water used by vegetation of all types were removed at one point, there would probably be little problem in assigning an additional streamflow for the fisheries below the point of withdrawal. However, because of the incremental and erratic pattern of water withdrawal, it is very important that in-stream flows for the fishery are defined in such a way that no part of the fishery is shorted. For example, a minimum fishery flow for the Tongue River might be assigned as 2.83 cms. (100 c.f.s.). Downstream irrigation for the month of July would be about 6.67 cms. (236 c.f.s.). Yet, if 6.67 cms. were released from the Tongue River Dam, the lower 155 km. of river would contain less than the recommended streamflow. Theoretically, the discharge would approach zero about 47 km. (30 miles) above the mouth. Failure to consider water use by riparian vegetation and upstream water users in this example, would not only deplete the fishery for the lower half of the river, but would probably destroy the lower one sixth of the river. Therefore, it is not enough to simply define a fishery flow alone. The specific area of the river that requires this flow must also be defined. In the case of the Tongue River, this area would be downstream from the T & Y Diversion. In-stream flows for vegetation must be considered additive, not complimentary. The complimentary approach will most certainly lead to deterioration or loss of the fishery, riparian vegetation, and perhaps even irrigated crops, in the lower part of the basin.

Failure to account for water withdrawal by riparian vegetation will itself result in a water deficiency, particularly during the months of July and August. While downstream water users are guaranteed adequate irrigation water by priority water rights, the riparian community is protected by an enormously permeable floodplain. As long as the riverbed is not dry, the trees will remove water from the river.

This discussion should not be interpreted as an argument for the defoliation of the floodplain in an attempt to reclaim water. It has been shown that riparian vegetation accounts for only about 10% of the total vegetational water requirement. Thus, elimination of the riparian community (no small task in itself) would at best increase the available water supply by about 10%. Bowie and Kam (1968) found that eradication of riparian vegetation from a stream in Arizona resulted in only about a 6% savings of water. They noted that evaporation caused the initial decrease in water volume, followed rapidly by a regrowth of riparian vegetation which was virtually impossible to control. Considering the benefits derived from riparian vegetation, elimination of floodplain vegetation can not be justified as a means of saving water. However, water use by riparian vegetation must be considered an additive in-stream flow requirement, if other in-stream uses are to be protected.

References

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CHAPTER 10: SEDIMENT TRANSPORT

Introduction

Sediment transport and sedimentation are usually considered to be subjects within the broad study of water quality. However, the problems caused by sediment particles in motion are considerably different from those caused when sediment ceases to move. It is necessary, therefore, to differentiate between the factors which lead to sediment movement and deposition, and the respective water quality problems associated with each.

Sediment is transported in streams by several mechanisms: 1) Suspension; the particles are supported by the surrounding fluid throughout the entire motion; 2) Saltation; particles are plucked or bounced into the flow and then return to the bed after travelling a short distance; and 3) Surface creep; particles roll or slide along the bed. Sediments moving by saltation and surface creep are primarily supported by the bed and are termed "bedload". Particles supported primarily by the fluid in motion are referred to as "suspended load". For some particle sizes there may be a considerable interchange between the suspended load and the bedload (Stalnaker and Arnette, 1976). Generally, particles in the suspended load tend to be smaller than the particles moving as bedload. Those particles in the suspended load which are finer than the bulk of the bed materials are termed "washload". This fine grained suspended material usually passes through the channel with little more than a transient impact (Einstein, 1950).

Washload is a primary cause of turbidity in streams, and is related to several water quality problems. The most familiar of these is the removal of fine particles from drinking water supplies. The same type of sediment is often responsible for plugging nozzles on sprinkler irrigation systems. Turbidity is an important factor in the aquatic ecosystem, for it reduces the visibility of sight feeding predators. Continuous high turbidity may play a selective influence against the sight feeders, such as smallmouth bass, and favor carp and other bottom feeders (Sigler, 1968; Cahn, 1929).

Generally, the amount of bedload and settleable suspended load is a small part (on the order of 10%) of the total sediment load. However, with respect to channel character and the aquatic ecosystem, these are the most important components. Many aquatic organisms have rather specific substrate requirements during at least a part of their life histories. It is a generally accepted axiom of aquatic biology that the areas of highest insect productivity are those with large, loose substrate materials, free of sand. The least productive areas are those over which the substrate is sand or gravel (Percival and Whitehead, 1929; Wene and Wickliff, 1940; Sprules, 1947; Cummins, 1964; Thorup, 1964; Gore, 1976). Some species of fish are likewise substrate oriented, and are severely limited when their preferred substrate becomes inundated with finer material. Clay (1962) states that the stonecat is extremely sensitive to sedimentation, and is most successful where the current velocity is sufficient to prevent the accumulation of sand and gravel. The rock bass (Ambloplites rupestris) and smallmouth bass (Micropterus dolomieui) both prefer a rocky substrate, but are not as adverse to sand bottoms as the stonecat (Scott, 1949; Hubbs and Bailey, 1938; Reynolds, 1965).

In addition to the obvious effects of sedimentation of riffle areas on the riffle dwelling species, movement of bed materials is crucial to other stream areas. The formation and maintenance of pool areas is largely a function of the scouring of these areas during the spring runoff. In the absence of this annual scouring cycle, pool areas will gradually fill with sand and silt. Pool areas are also primary catch-basins for organic sediments produced within the channel, or entering from sewage outfalls, feedlots, leaf litter, and other sources. These organic sediments may form sludge deposits capable of depleting the dissolved oxygen content for some distance downstream (Velz, 1970; Mills, Starrett, and Bellrose, 1966).

Sedimentation has been shown to cause dramatic declines in the reproduction of many species. Deposition of fines over spawning grounds reduces the infiltration rate of oxygen-rich water to eggs deposited on, or in, the gravel spawning beds (Silver, Warren, and Doudoroff, 1963). Salmonids are especially vulnerable to sedimentation because they bury their eggs in the gravel. However, many warm-water species would likewise be affected if sediment were deposited on their nests at a higher rate than the guarding male could remove it. Members of the catfish family which select channel cavities as spawning sites would also be deleteriously affected, as would several genera of cyprinids. Species which spawn by broadcasting eggs would probably be affected the least, particularly if the eggs are rapidly water hardened and did not stick to the bottom.

A common problem associated with aggradational alluvial streams is the deposition of sediment as mid-stream bars. This frequently results in increased bank erosion as the river is forced to split around the bar. The formation of mid-channel bars is explained in some detail by Culbertson, et. al. (1967). Pools are scoured at the outside of meanders, primarily at higher stages. Material scoured from the pools tends to deposit and form bars where the velocity becomes uniform in the crossover between meander bends. During falling stage, the crossing bar is slowly scoured due to locally increased slope, until equilibrium is reestablished at the lower discharge. Thus, pools are scoured at high discharges, and filled at low discharges, while cross-over bars have the opposite tendency. It should be stressed that pool scouring is not the only source of sediment for the formation of cross-over bars. However, it is possible that an absence of pool scour will eventually result in a stream with little variation in bottom configuration.

Sedimentation can also cause major problems with man-made structures and facilities along the riverside. Culbertson, et. al. (1976) shows that deposition commonly occurs between bridge pilings and in some cases can increase the susceptibility of the bridge to damage by ice jams, drift, and flood waters. Pool scour is also important for the efficient use of sprinkler irrigation systems. Without annual scouring of the pool housing the pump intake, the pump will pick up increasing amounts of sand and silt. The result will be that pipes and nozzels will be plugged with sediment with greater frequency, and possibly will result in damage to the pump itself.

In addition to sprinkler irrigation, flood irrigation may be affected by inadequate sediment removal. There are several small diversion dams along the Tongue River which are used to feed canals for flood irrigation. These diversion dams are, in a sense, large pools. During low water, the pools collect large amounts of sediment, which is scoured only at relatively high flows. Failure of the river to scour these diversion dams will result in 1) complete filling of the diversion basin with sediment, and 2) introduction of large amounts of sediment into the canal system. This may result in higher operating costs to the water users, who will be forced to dredge the diversion basin, the canal system, or both, to maintain an efficient irrigation system.

Sediment Sources

Many factors must be considered in the evaluation of the potential sediment problems of a river. Some factors are considered hydrologic; these are parameters characteristic of the drainage basin, the climate, geology, lithology, vegetation, and land use practices which contribute to, or retard, the rate of sediment removal from the drainage. Other factors are hydraulic, and relate to the capacity of the river to remove a certain amount of sediment at a given discharge. In order to maintain an established equilibrium condition in the river, it is important that the hydrologic parameters of the watershed are balanced by the hydraulic capabilities of the stream. Cordone and Kelly (1961) found that the greatest damage from sedimentation occurs when sediment enters the stream at other than high flow periods, and therefore water velocity was insufficient to remove the added load.

Climatic Factors:

The climate of the NGP contributes significantly to the sediment problems of many of the rivers. Langbein and Schumm (1958) found that regions receiving around 38 cm. of rain per year have the highest rates of sediment yield per unit area. Such areas received sufficient rainfall to cause active surface erosion, but not enough to grow an adequate vegetative cover to retard runoff or stabilize the soil. The NGP region is also frequently subjected to violent thunderstorms of small areal extent. When these storms occur in tributary basins, they can result in extremely high concentrations of sediment in the feeder streams, with little significant increase in discharge in the main stem to handle the added load. For most watersheds, more than one-half of the soil losses are attributable to such small storms, with return periods of less than one year (Piest, 1965).

The climate also contributes to the erosion process during the early spring. The so-called "lowland runoff" from snowmelt occurs in the lower parts of the drainage during late February and early March. During the early phases of snowmelt, the ground is frozen and relatively little sediment is added to the streams. Later, the top layers of soil are thawed, but a deeper frost zone is still present 5 to 10 cm. below the surface. This frost zone impedes the infiltration of water, leaving the thawed layer virtually saturated and easily eroded. Runoff during this period usually results in very high concentrations of sediment in the streams. A particularly interesting aspect of the lowland runoff is that the streambeds of many of the feeder streams are covered with a sheet of ice 20 - 30 cm. thick, and frozen to the bottom. During the period of lowland runoff, these streams become almost frictionless conduits for sediments and water, and lose little of either before they enter the main stem.

Geologic Factors:

The geology of the Tongue River basin plays a major role in both the hydrologic characteristics of the watershed and the hydraulic characteristics of the river. Structurally, the basin has been elevated to the south by the Big Horn uplift (Baker, 1929). As a result, the Tongue River has a slightly increased gradient which has led to incision and armoring of the bottom throughout much of its length. The asymetry of the valley and the occurance of gravel deposits on the west side of the streams, indicates that the region has been tilted eastward subsequent to, or during, the Pleistocene (Pierce, 1936; Bass, 1932). The presence of numerous gravel covered benches and stream-cut terraces along the river indicates that uplift of the basin has been intermittent. Because of basin tilting and uplift, tributaries entering the Tongue River from the south are longer, and are assumed to be head-cutting. In any event, they carry much more sediment than those entering from the north.

Differences in lithology account for the large variations in sediment yield typical of the Tongue River valley. In the upper valley, roughly from Brandenberg to the Tongue River dam, the dominant surface lithology is the Tongue River member of the Fort Union formation. This unit is composed of light colored sandstone and interbedded gray shale. Several coal beds are also found in the Tongue River member. However, the outstanding feature of the unit is the red clinker of the Roland coal bed, which marks the contact between the Fort Union and Wasatch formations. This clinker bed plays an important role in the hydrology of the upper basin. Because it is fractured, and extremely resistant to weathering, much of the moisture falling into the upper basin infiltrates very rapidly. This results in a rapid throughflow, with little erosion. Thus, most of the water entering the Tongue River from this lithologic unit does so as groundwater, and is relatively sediment-free.

In contrast, the underlying Lebo shale member of the Fort Union formation is composed of loosely consolidated, somber shaded shale beds with lenses of gray and yellow sandstone. This member forms a large portion of the Tongue River Valley north of Brandenberg. The Lebo shale weathers easily and is subject to rapid erosion. In addition, many of the hillslopes in the Lebo are bare of vegetation, which undoubtedly aids the erosion process. The Lebo member contributes a large amount of sediment to the Tongue River, most of it from the shaly horizons, and carried primarily as washload.

Perhaps the greatest source of coarse sediment for the Tongue River is the valley alluvium through which the river flows. Although composed of unconsolidated sand and gravel, the banks of the Tongue are quite stable due to the network of tree roots along the banks. In many places the river impinges against high, steep, and unvegetated alluvial terraces. These terraces are composed of unconsolidated sand and gravel, and are particularly prone to slumping. Such slumps are important sediment sources, because unlike the other major sediment sources, the introduction of this material is often totally unrelated to the discharge of the river. While most of the primary sediment-runoff events are caused by, or accompanied by, a rise discharge, the slumping of river terraces is not. Unfortunately, the amount of sediment entering the channel in this manner is virtually unquantifiable without a long, stochastic examination of the process.

The study of sediment transport in the Tongue River had several interconnected objectives. The first objective was the examination of the hydrology of the watershed in order to 1) determine the characteristics of the various sediment sources; 2) determine the relative importance of each sediment source in the contribution of coarse sediment to the river; and 3) locate the river section where the river hydraulics are least able to carry the sediment load. The second broad objective includes 1) the assessment of the sediment transport characteristics of the critical section; 2) the determination of the discharge at which active scour begins; and 3) the comparison of this flow requirement with the flow required for the spawning of the indicator species.

Methods and Materials

All suspended sediment samples were taken with a US DH-48 sampler with a 1/4" nozzle. Samples were collected by the equal transit rate (ETR) method as described by Guy and Norman (1970). Bedload samples were taken at regular intervals across the stream with a Helley-Smith pressure difference sampler (Helley and Smith, 1971). A one minute sampling period was allowed for each vertical bedload sample. Sampling was limited primarily to wadeable flows, as wading afforded better control of the Helley-Smith sampler.

All samples were analyzed according to the methods described by Guy (1969). Suspended sediment samples were wet-sieved through a 62 micron sieve to separate the sand and silt-clay fractions. The sand fraction was filtered with a Gooch crucible, while most silt-clay samples were evaporated. In order to minimize problems with dissolved solids in the evaporated samples, each sample was allowed to settle, decanted, and washed with distilled water several times prior to evaporation. Organic material was removed by treatment with 7% H_2O_2 prior to evaporation. Samples were heated to dryness, and placed in desiccators until cool. Then samples were weighed to the nearest milligram.

Bedload samples were treated repeatedly with hydrogen peroxide solution (7%) to remove the large amounts of organic sediment included within the sample. Organic-free samples were washed with distilled water, heated to dryness, and oven baked for at least one hour at 110 °C. Samples were then cooled and dry-sieved through nested sieves mounted in a motorized shaker. Each size fraction was then weighed to the nearest 10 milligrams.

Results and Discussion

Sampling during the 1975 runoff was concentrated on the tributaries draining both the Lebo shale and Tongue River lithologies. Several spot samples were also collected within the Tongue River at Birney, Viall Ranch, SH Ranch, and Orcutt Ranch. Results of the analysis of suspended sediment samples are summarized in Table 10-1. Table 10-2 summarizes the analysis of bedload samples taken at the same time.

Results are not listed for the Birney section, although it was sampled several times. At all flows, the suspended load was quite low at Birney, and bedload movement was imperceptible. This condition probably reflects the influence of the Tongue River dam, which removes most of the sediment a relatively short distance above Birney, and the armored condition of the streambed around Birney.

The influence of lithologic differences between the Tongue River member and the Lebo shale is especially apparent in Table 10-1. Hanging Woman Creek and Otter Creek, which both drain the Tongue River member, usually carried a very low concentration of sediment. The concentration of suspended sediment in Hanging Woman Creek ranged from 26 to 340 mg/l. In Otter Creek,

Table 10-1: Analysis of Suspended Sediment Load for Several Locations on the Tongue River and tributaries.

Stream (Location)	Drainage* (Lithologic Unit)	Discharge cms.	Concentration mg/1	Load TPD	Size Composition % of Total	
					Clay	Sand
Tongue River						
(Viall)	Tfut	12.8	90	100	100	0
		15.8	45	61	100	0
(SH)	Tfut/Tful	17.5	167	253	100	0
(SH)		33.9	505	1480	75	25
(Orcutt)	Tful	13.6	83	98	100	0
		21.9	402	760	78	22
		30.0	496	1290	78	22
Hanging Woman Cr.	Tfut	.3	185	6	100	0
		.4	338	12	100	0
		.7	26	2	100	0
Otter Cr.	Tfut	.6	43	3	100	0
		.7	44	3	100	0
Brown Cr.	Tful	.1	2050	25	99	1
		.5	28600	1400	45	55
Haddow Cr.	Tful	.5	17170	742	92	8
		.5	2400	118	98	2
		.8	7120	492	92	8

*Tfut refers to Tongue River member of Ft. Union formation; Tful refers to Lebo Shale member.

Table 10-2: Analysis of Bedload for Several Locations on the Tongue River and Tributaries.

Stream (Location)	Discharge cms.	Metric Tons per Day, by Size Class						
		8-4 mm.	4-2 mm.	2-1 mm.	1-.5 mm.	.5-.25 mm.	.25-.125 mm.	Total
Tongue River								
(Viall)	12.8	.50	1.30	3.10	4.40	2.60	.60	12.50
	15.8	.01	.02	.08	.60	2.00	.30	3.00
(SH)	17.5	.11	.22	.38	1.30	3.70	2.70	8.40
	33.9	.24	.27	1.20	3.60	4.50	2.60	12.40
(Orcutt)	13.6	.10	.30	1.10	4.40	8.20	3.30	17.40
	21.9	.97	.94	2.80	5.20	4.60	4.80	19.30
	30.0	1.20	1.90	4.30	9.30	13.80	9.60	40.10
Haddow Cr.	.5	0	0	.004	.01	.23	.63	3.10
	.9	0	.01	.005	.02	.42	2.60	.87
Jack Cr.	.1	0	0	0	.003	.017	.049	.07
Brown Cr.	.5	0	0	0	0	0	.310	.31

the concentration varied little from 45 mg/l. The suspended sediment in both streams was extremely fine, almost colloidal. Bedload movement was not detected in either stream. The primary load of both streams is apparently in the form of dissolved solids.

The concentration of total dissolved solids (TDS) in Hanging Woman Creek ranged from 1000-2900 mg/l, while Otter Creek had an average TDS concentration of 1400 mg/l. In comparison, the TDS concentration for the Tongue River and most of the lower tributaries varied only slightly from 500 mg/l. This fact tends to confirm the hypothesis that rainfall in the upper valley reaches the mainstem primarily as groundwater.

Conversely, the load carried by tributaries draining the Lebo shale is composed primarily of suspended sediment. For most of the streams in this part of the drainage, the suspended load consists a great deal of washload, with less than 10% sand in most of the samples. The high sand concentration in the Brown Creek sample probably reflects the influence of frost, as discussed earlier. In some instances, the daily load of each of these small tributaries can be quite large. Loads ranging from 500 to 1000 metric tons per day were not uncommon; however, most of the streams in the lower drainage are ephemeral and carry these high loads for only a short period during the spring. In addition, appreciable amounts of coarse sediment occurred in suspension only as the creeks approached bankfull stage.

The contribution of coarse sediment by the bedload of the small tributaries is minor. Table 10-2 shows that most of the bedload is made up of fine to medium sand (125 to 250 microns median diameter), and the load from each stream was usually less than one metric ton per day.

From the data in Table 10-1 and 10-2, several conclusions were reached concerning the nature of sedimentation in the Tongue River Valley. First, the contribution of coarse sediment (larger than 125 microns, median diameter) by the tributaries throughout the length of the river, is inconsequential. A large amount of sediment enters the river from the tributaries, but it is mostly washload. Secondly, the source of most of the coarse sediment is from in-channel deposits, bank caving, and terrace slumping. Of these, only slump material enters the river for reasons other than high flow. Thirdly, the river bed becomes less stable and more prone to aggradation in the lower parts of the basin. This is the result of several factors: 1) a general reduction in slope, resulting in less energy available to move sediment; 2) a larger source of coarse sediment with the capability of entering the river (terraces and banks are perhaps least stable in this part of the river); and 3) an increase in channelization in the lower reaches. Sediment is actively scoured from the channelized reaches, even at low flows, and is quickly deposited where the channelization ends. Therefore, it was concluded that the greatest potential for sediment deposition and aggradation would probably occur in the lower 20 km. of the Tongue River, below the confluence of Pumpkin Creek.

During the spring of 1976, a sediment sampling station was established in an unchannelized portion of the lower river near the Ft. Keogh Range Experiment Station (USDA). Samples were collected at two to three day intervals, from the end of March through the middle of June. The purpose of the sampling was to attempt to determine the discharge required to initiate bed-material movement in the section. The sampling area was located at the foot of a large pool, just upstream from a channel constriction which acted as a control. During the sampling period tributary runoff was intermittent and minimal, and the banks immediately above the section were fairly stable. It was assumed that a substantial increase of coarse material in either the bedload or suspended samples would be an indication that scour had been initiated in the pool, and that most of the sediment collected would therefore be channel derived.

Sediment rating curves were constructed for both the total suspended load and bedload, and the constituents of each type of load. These curves are included in Appendix K. The straight lines on each figure in Appendix K are the least square fit of the data.

Several general trends are apparent from the curves in Appendix K:

1) The total suspended load is so dominated by silt-clay sized particles, that there is little difference between curves K-1 and K-2, or K-4 and K-5. The degree of scatter for these curves indicates that the concentration and load of silt-clay particles are related to exterior processes. They are related to discharge by virtue of an increase in both washload and precipitation.

2) The scatter of points for suspended sand particles (Figures K-3, K-6) is smaller, indicating less randomness in the relationship between suspended sand load and discharge.

3) The total bedload curve likewise has little scatter, indicating a non-random process. The scatter becomes greater as particle size increases. At the flows sampled, it is likely that the capture of larger bedload particles is largely accidental and random.

4) The trend-fitted curve (dashed line) for Figures K-3 and K-6 suggests that the occurance of fine sand in suspension is accelerated at flows between 18 and 25 cms. This discharge range may initiate the scour of fine sand from the pool.

5) A similar relationship is suggested in Figure K-8, where there is a clustering effect of data points. Between 18 and 25 cms. there appears to be a significant increase in the movement of particles up to 250 microns median diameter.

6) In general, the slopes of the least square lines become smaller as the particle size increases. This would indicate that true bed mobility

has not been attained by discharges up to 25 cms., and that the coarse material collected may be considered as background.

It must be stressed that the purpose of selecting a discharge for the removal of sediment is not to cause degradation of the channel, but only to assure scour of the pools. It may be stated unequivocally, that total bed scouring (bed mobilization) had not occurred at 25.5 cms., the highest flow sampled. However, the movement of fines, deposited on the bed, apparently was initiated at flows between 18 and 25 cms.

Unfortunately, there is no sharp line of demarcation, no sharp break in curve, that would suggest a single flow capable of scouring the pools. Rather, the initiation of pool scour is represented only by a broad band of discharges. A commonly accepted axiom of hydrology states that there is an inertial effect which must be overcome before sediment will move. Stated another way, it takes more energy to initiate movement than it does to sustain it. The axiom applies equally to suspended load and bedload. This inertial effect may be involved in the splitting of the data clusters at the 18-20 cms. level for the fine to medium sand represented in the figures of Appendix K.

It is suggested therefore, that 18 cms. be considered the lowest discharge at which pool scour would occur. However, 20 to 25 cms. would be required for accelerated scour capable of removing the amount of sediment deposited in the pools over a year. At flows up to 25 cms. it is likely that the sediment moved is recently deposited, loosely packed, and readily transportable. In order to move the coarser, and more firmly packed, bed materials underlying this deposit, flows in excess of 30 cms. would probably be required.

Time and Scour Efficiency:

Data in Appendix K show that even at fairly low discharges fine sand particles were in motion. Once the critical shear stress of individual particle sizes has been exceeded, only the rate of transport is affected by increased discharge. In terms of in-stream flows, particularly where reservoir releases are involved, this point becomes crucial. If X amount of sediment must be removed from a stream section, it might be removed by a discharge of Q cms., maintained for 30 days. The same amount of sediment might also be removed with a discharge of 10 Q cms., maintained for only 3 days. The release of the 10 Q discharge would obviously be the more efficient use of water for sediment removal. However, the flow of 10 Q might also be disastrous to the in-stream resources which are to benefit from sediment removal. A balance must be struck, therefore, between the most efficient rate of sediment transport and the discharge tolerances of all other in-stream resources.

Associated with this concept is the preferable rate of rise and drop in stage. It has been demonstrated that rapid changes in water level are deleterious to insects and fish alike (Giger, 1973; Hooper, 1973; Hoppe and Finnell, 1970). Little is gained by suddenly increasing the flow in hopes of causing instantaneous scour. A sudden large drop in discharge may cause coarse gravel, and other large sized sediment already in motion, to settle in areas normally filled with finer sediment. This would tend to make initiation of scour more difficult with each succeeding year. It is recommended, therefore, that the rate of change in discharge should not exceed 25% of the previous 24-hour discharge until such time as it is demonstrated that a faster change in stage is not harmful to other resources. The total time required for pool scour should be considered an integration from low flow up to the desired scouring flow, the duration of scouring flow, and the retreat back to low flow. Since a large amount of sediment will be removed during the rising and falling stages, the high flow duration may be reduced significantly.

Methodological Assessment of Sediment Transport Studies:

The empirical method used in the assessment of sediment movement is the simplest and most reliable method available. It is not without its limitations, however. The use of hand-held wading equipment restricted sampling in the Tongue River (Ft. Keogh Section) to discharges less than 25 cms. At higher flows, wading became difficult and much of the equipment unmanageable. The Helley-Smith sampler, in particular, requires good control in order to take "clean" samples. Although weighted toward the tail, and collared properly, the sampler still had a tendency to nose into the bed if care was not taken. This problem obliged the researchers to station oneself so that the sampler could be controlled through its entire descent. Sampling from a boat was attempted, but abandoned because of this problem.

One of two design modifications might help make the Helley-Smith sampler easier to control in large, deep rivers:

1) Attachment of a 1/4 " steel plate, to the rear stabilizer fin, which would weight the tail considerably without changing the hydraulic characteristics of the sampler.

2) Affixing a "spoiler" to the stabilizer fin, allowing water pressure to force the tail down.

The empirical method of sediment analysis has many of the shortcomings of the multiple transect method of assessing fishery flows. It requires special equipment, laboratory space, and a considerable time investment. A partial solution to the problem may lie in the use of sediment transport models.

There are several methods used to assess sediment movement in streams. The simplest of these is the comparison of the mean channel velocity at various discharges with the velocity required to move a certain size particle.

Although commonly used, this method is not very accurate, for it does not consider the effects of packing and inertia, or the fact that shear stress is also related to depth.

Another commonly used method is the computation of the tractive force at various flows for comparison with the tractive force required to move particles of a given size (critical tractive force). The expression for the average shear stress in a channel is:

$$\tau = \omega R s \qquad \text{(Eq. 10-1)}$$

Where, ω = the specific weight of water, R is the hydraulic radius, and s is the slope of the energy gradient. In many hydraulic computations this slope is approximated by the slope of the water surface, as the two are parallel in uniform flow.

Lane (1955) has developed criteria for the movement of noncohesive materials based on critical tractive force. For materials with median diameters smaller than 5 mm., the critical tractive force may be determined from Figure 10-1.

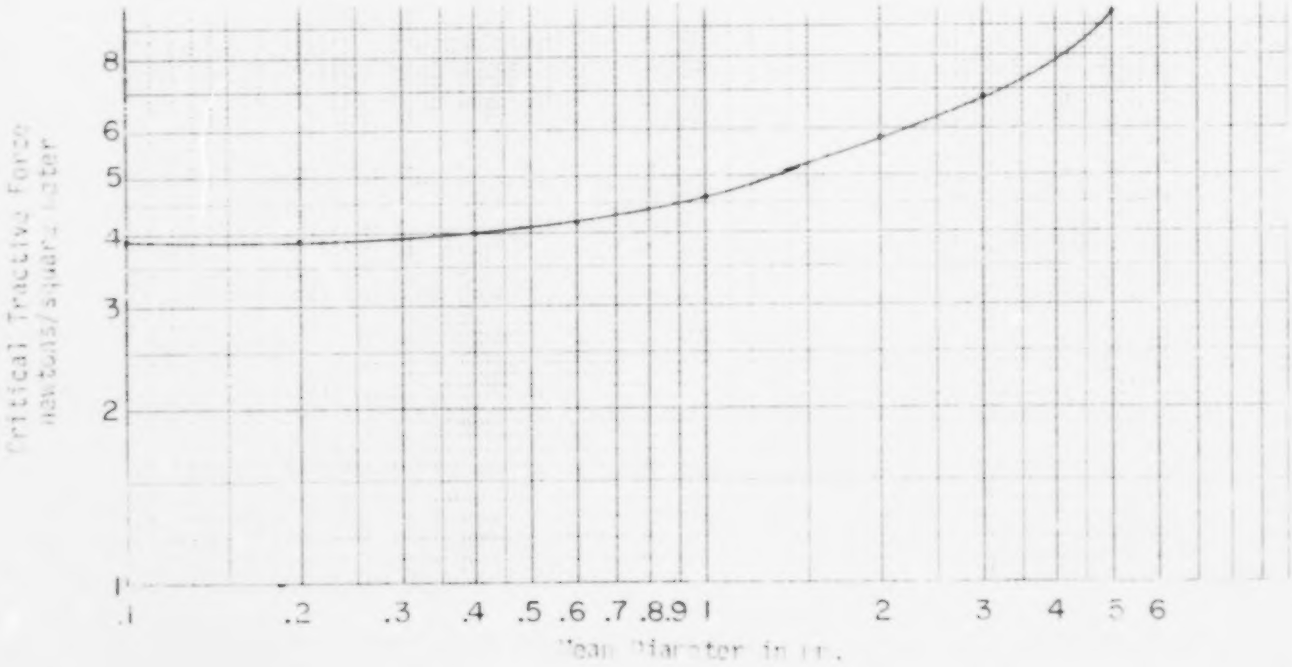

Figure 10-1 Criteria for scour, median diameter of particle less than 5 mm. From: Lane, E.W. 1955. "Design of Stable Channels," Trans. ASCE. 120: 1234.

The critical tractive forces designated in Figure 10-1 are applicable to canals and may not be appropriate for the non-uniform flow conditions of rivers (King and Brater, 1963). Leopold, et. al. (1964) give the following equation as a means of finding the critical tractive force:

$$\tau_c = K\,(\sigma - \rho)\ g\ D\ s \qquad \text{(Eq. 10-2)}$$

Where:

$K = \eta(\pi/6)$

η = a packing coefficient = $\dfrac{\text{number of grains} \times D^2}{\text{unit area}}$

σ = mass density of grain

ρ = mass density of water

g = acceleration of gravity

D = grain diameter

s = slope of energy gradient

If grain size and density are given in cm. and gm./cm^3 respectively, the units of critical tractive force will be in dynes per cm^2. If the grain size is in feet, and density in slugs per ft^3, the critical tractive force will be in lbs./ft^2. The operational weakness of the equation, as far as the field worker is concerned, is the determination of the value for the packing coefficient. Most values for critical tractive force are derived from flume data, wherein the size of the sediment particles are standardized. In rivers, the bottom sediment is usually a well mixed matrix of many particle sizes. Leopold (1964) suggests that the most practical method of determining a reliable estimate of τ_c would be one based on plotting the measured rate of transport for each size class against mean bed shear for a variety of conditions, and extrapolating the empirical relation to the intercept where transport rate equals zero.

Unfortunately, the critical tractive force method gives a value only for the competence of the stream. It tells little about the amount of sediment of different sizes in transit at different discharges. There are many sediment transport models available to achieve this end. However, most are quite complex, and descriptions of each are beyond the scope of this report. The reader is referred to the original reference organized to the model type designated below:

1. Critical shear stress:
    - A. Kalinske, A.A., 1947, "Movement of sediment as bed-load in rivers," Trans. Am. Geophys. Union, 28, (4). *
    - B. Chang, F.M., Simmons, D.B., and Richardson, E.V., 1965, "Total bed-material discharge in alluvial channels," U.S.G.S. Water Supply Paper 1498-I.
2. Bed-load function:
    - A. Einstein, H.A., 1950, "The bed-load function for sediment transportation in open-channel flows," Soil Cons. Serv. Tech. Bull. 1026.
    - B. Colby, B.R. and Hembree, C.H., 1955, "Computations of total sediment discharge, Niobrara River near Cody, Nebraska," U.S.G.S. Water Supply Paper 1357.
    - C. DeVries, M., 1965, "Considerations about nonsteady bed-load transport in open channels," Delft Hydraulics Lab. Pub. #36. *
3. Suspension:
    - A. Rouse, H., 1937, "Modern Conceptions of the mechanics of turbulence," Trans. ASCE, vol. 10. *
    - B. Bagnold, R.A., 1966, "An approach to the sediment transport problem from general physics," U.S.G.S. Professional Paper 442-J. *
    - C. Brooks, N.H. and Keck, W.M., 1963, "Calculations of suspended load discharge from velocity and concentration parameters, USDA Misc. Pub. 970, paper #29.
    - D. Tywoniuk, N., 1972, "Sediment discharge computation procedures," J. Hyd. Div., Proc. ASCE 98(HY3), 521-540. *

*Stalnaker and Arnette (1976) list these and several other sources. This list includes only the more readily accessible references.

The most important aspect of these models to the field worker (besides their proven reliability) is the nature of the data inputs required. Most of the models have all or some of the following data inputs in common:

1. Surveyed cross-sectional data.
2. Determination of energy gradient.
3. Determination of flow depth, hydraulic radius, and mean velocity for a number of discharges.
4. Particle size characteristics of bed, particle density, and porosity.
5. Temperature and density of fluid.

With the exception of items 4 and 5, the data requirements are essentially identical to those required by the Water Surface Profile Program as outlined in Chapter 6. Item 4 may be determined from three to five composite samples taken with a pipe sampler. Item 5 might require several water samples to determine a range of densities at different concentrations of washload. If critical tractive force is needed, it should probably be determined empirically by the method suggested by Leopold, et. al. (1964). The general conclusion must be made that a few additional data inputs, collected in the process of gathering information for the WSPP, would enable researchers to add sediment transport analysis to the hydrologic aspects of the WSPP. This would be a significant addition of information with little added field work.

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CHAPTER 12: GLOSSARY

advected heat loss: Removal of heat from a surface, typically by wind, through a predominantly horizontal motion.

aggradation: Progressive deposition of sediment within a channel or on the flood plain, resulting in an increased elevation of the streambed or flood plain.

allochthonous: Organic material entering the stream from outside sources; i.e. leaf fall.

armored streambed: A streambed in which all of the fine sediment has been removed, leaving only coarse material which cannot be transported.

association coefficient: A computational index used to determine the relative similarity of community structure for different communities.

association dendogram: A diagram which indicates the degree of similarity of community structure for different locations.

assymetric watershed: A drainage basin in which the lengths and stream orders of the tributaries draining one side of the basin are significantly different from those on the other side.

autochthonous: Organic material produced within the stream; i.e. algae.

base flow: The minimum flow requirement for the preservation of any instream resource; a survival flow requirement.

bedload: Sediment particles which, when in motion, are supported primarily by the bed.

biomass: The amount of living matter in an area, or volume, of habitat.

Bowen ratio: The ratio between the portions of the total available energy expended to sensible heat to the air and to the evaporation of water.

canopy: The foliage overstory of trees or brushy plants; the area covered by leaves and branches of trees.

channel constriction: A narrowing of the channel which may act to control upstream flow.

clinker: A very hard and resistant rock formed from shale which has been baked by burning coal beds; fused residual minerals from the burning of the coal bed.

cm.: Centimeters (distance).

cms.: Cubic meters per second (discharge).

cm./sec.: Centimeters per second (velocity).

COCD: Centroid of optimum conditions of diversity; a point on a two-dimensional surface representing the depth-velocity, or turbulence-substrate conditions most conducive to high aquatic invertebrate diversity.

composite map: A scaled, plan view of a channel area, delineating areas suitable for habitation or use by a certain indicator species.

conveyance area: The cross sectional area of flow, normal to the direction of flow.

critical area: A stream area, reach, or habitat type which shows the greatest variation in hydrologic parameters, such as depth and velocity, with changes in discharge.

critical tractive force: The force required to initiate movement of a given sediment size.

degradation: The lowering of the streambed elevation by progressive scour of the bed.

diurnal periodicity: A behavior pattern which is recurrent on a daily basis.

diversity: A statistic describing the relative abundances of different species in a collection of S species, sometimes refers to the number of different species.

drift, invertebrate: Refers to aquatic invertebrates which have released from, or have been swept from, the substrate and move or float with the current.

effective precipitation: The amount of precipitation required to significantly change soil moisture; total precipitation adjusted to reflect interception and immediate evaporation.

energy gradient: The slope of the line representing the change in elevation of the total energy head. For uniform flow, the slope is approximated by the slope of the water surface.

ephemeral stream: Any stream which transmits water intermitantly during the year, usually in response to snow melt or heavy rainfall.

evapotranspiration: Transfer of moisture from a vegetated surface to the atmosphere.

evapotranspiration deficit: The approximate difference between the rate of precipitation and the rate of evapotranspiration, representing the amount of water supplied by the river for evapotranspiration.

flow criteria: The velocity range, depth range, and substrate type most commonly associated with a given species.

Froude number: The ratio between inertial forces and gravity forces in running water; used as an index of turbulence.

hydraulic depth: Ratio of the conveyance area to the greatest width.

hydraulic gradient: Slope of the water surface

hydraulic radius: The ratio of the conveyance area to the wetted perimeter. For wide, shallow streams this approximates the hydraulic depth.

hydrologic contour map: A scaled planimetric map showing isolines of equal depths or equal velocities, or delineating areas of common bottom types. Maps are read like topographic maps.

ice, anchor: Sheet-like crystal aggragates which grow outward, from submerged objects as a result of radiational cooling of the streambed.

ice, frazile: Surface-formed, thin and circular, disk-shaped crystals of ice which occur wherever an open water surface is supercooled. Frazile ice may coalesce to form a surface ice sheet.

ice, surface: A solid ice layer in complete flotation over a body of water. First formed by the coalescence of frazile ice crystals, but thickened primarily by conduction of heat through the ice to the atmosphere.

incised stream: A stream which has cut through bedrock or into its streambed to such an extent that the meander pattern is quite stable.

indicator species: Here used to describe a species which is more sensitive to changes in hydrologic or substrate parameters than other species, and which is an inhabitant or periodic user of critical area habitats. It is assumed that if the flow requirements of the indicator species are met, the requirements of all other species will also be met.

instantaneous flow: The volume of water passing any point in an instant of time. Units are in cubic meters per second.

kite diagram: A diagram describing the relative abundance and distribution of a species within its range.

Latent heat of fusion: The negative heat transfer required to change the state of water from liquid to solid.

micro-profile: The three-dimensional "topography" of the substrate providing habitat for aquatic invertebrates.

micro-profile index: A statistical description of the roughness and surface area availability of the substrate.

multiple transect analysis: The process of utilizing hydrologic data measured across several transects over a critical area to assess the available habitat area at different discharges.

optimum flow: The discharge which provides the greatest amount of habitat area for a given indicator species and critical area.

permeability: The relative ease with which water can move through earth materials; the rate of discharge per unit area, through earth materials, under controlled hydrologic conditions.

phototaxis: Orientational movement of organisms where light is the directive factor.

point depth: The vertical depth at a specific location in a channel cross-section.

point velocity: The mean velocity of the vertical water column at a specific location in a channel cross-section.

porosity: The ratio between the volume of void space and the total volume of earth material.

riparian vegetation: Vegetation situated in close proximity to a river and dependant upon the river, or influent groundwater, for its water source.

roughness coefficient: A correction factor incorporated into hydraulic models to account for the flow resistance of the bed and banks.

sediment yield: The amount of sediment, per unit area, eroded from a watershed each year.

sinuosity: The ratio between the length of a river and the length of its valley.

soil heat flux: Loss or gain in heat energy from heating or cooling of the soil.

steady flow: Flow in which the depth or water level does not change during a specified time interval.

stream control: Any feature of the channel configuration which controls the flow in such a way that it restricts the transmission of water.

streamflow reservation: Essentially a water right granted to a state agency to protect an in-stream flow for the beneficial use of fish and wildlife, maintenance of water quality, preservation of natural channel processes; or to honor and support existing water rights.

thalweg: The line following the lowest part of a valley, usually following the deepest part of the channel.

thermal conductivity: The ability of a substance to transmit heat. Used primarily to describe the loss of heat through a thickness of surface ice.

tractive force: The effective component of the gravity force acting on a body of water, parallel to the channel bottom and equal to ωALS, where ω (omega) is the unit weight of water, A is the wetted area, L is the length of channel reach, and S is the slope.

transmissivity: The ease with which water can move through a thickness of earth or aquifer materials; the discharge rate for a thickness of aquifer of unit width under controlled hydraulic conditions.

turbidity: The degree of opacity or cloudiness of a body of water due to the suspension of particulate matter. Usually caused by sediment but may also be caused by algae.

uniform flow: Flow in which the depth of water is equal at every section of the channel.

washload: That portion of the suspended sediment load which, because of its small settling velocity, is held in suspension as essentially colloidal particles.

water envelope: The layer of liquid water occuring between the bed of a stream and the underside of a surface ice sheet.

APPENDIX A

HYDROLOGIC CONTOUR MAPS

REARING AREAS

1. Direction of flow is from top of page to bottom
2. For easier interpretation, depth contours are indicated by vertical typeface. Velocity contours are indicated by slanting typeface.
3. Hatchered areas on contour maps indicate isolated areas of reduced depth or velocity, depending on the type of map.
4. Dashed lines indicate edge of water, either at banks or on exposed bars.

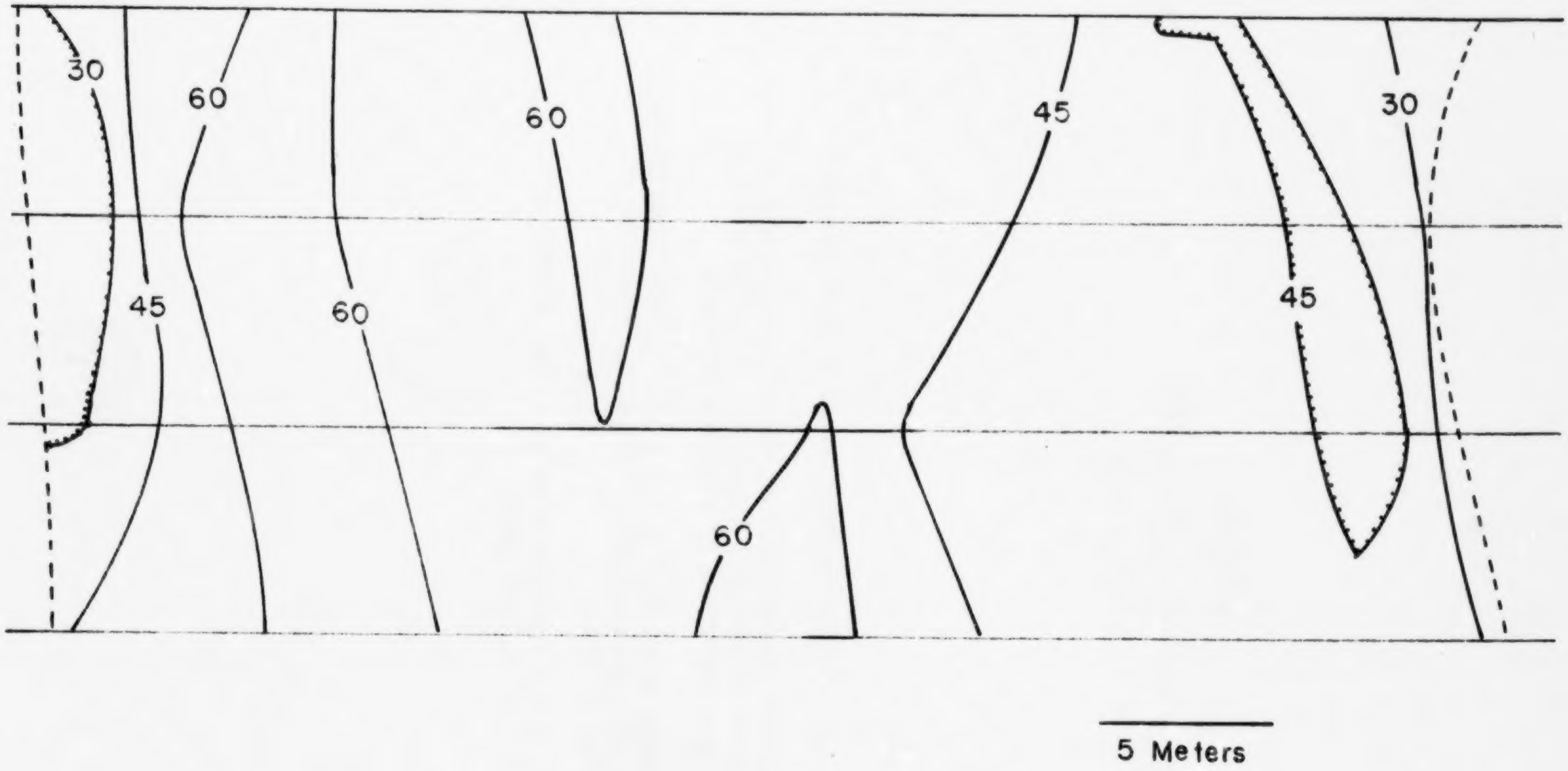


Figure A-1: Depth Contour Map from the Viall Mapping Section. Depths in cm. Discharge = 19.4 cms.

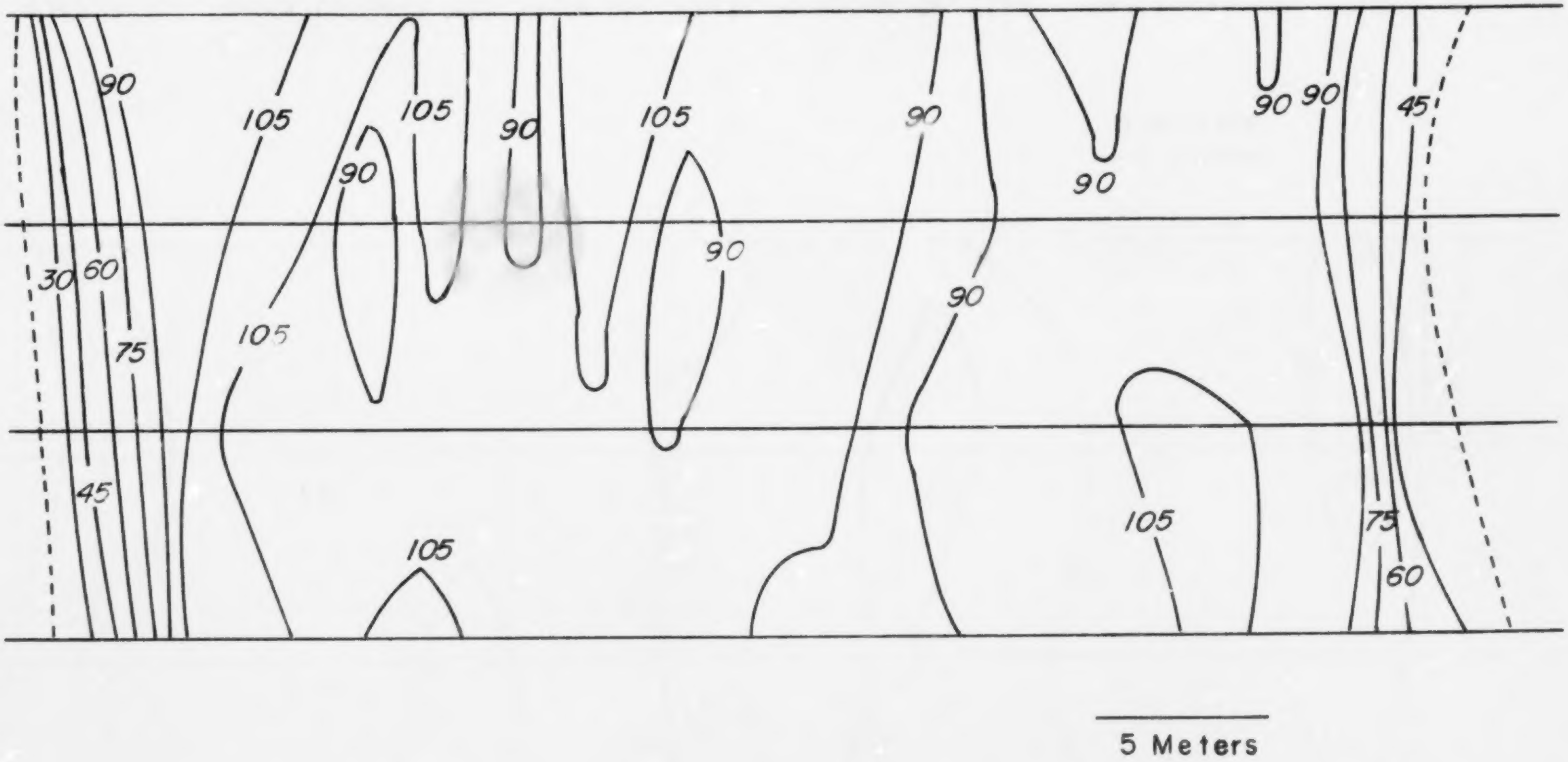


Figure A-2: Velocity Contour Map from the Viall Mapping Section. Velocities in cm./sec. Discharge = 19.4 cms.

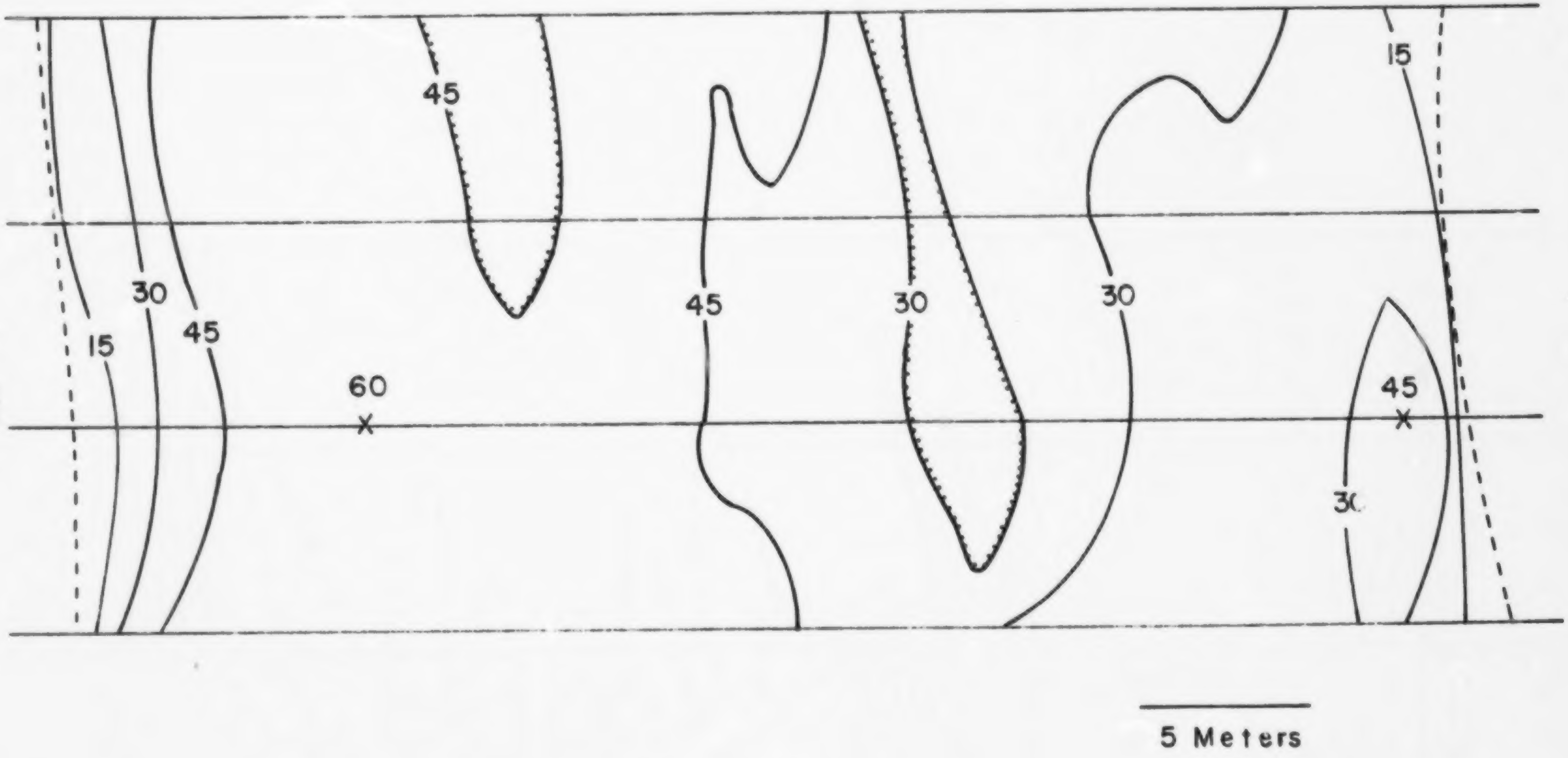


Figure A-3: Depth Contour Map from the Viall Mapping Section. Depths in cm. Discharge = 12.0 cms.

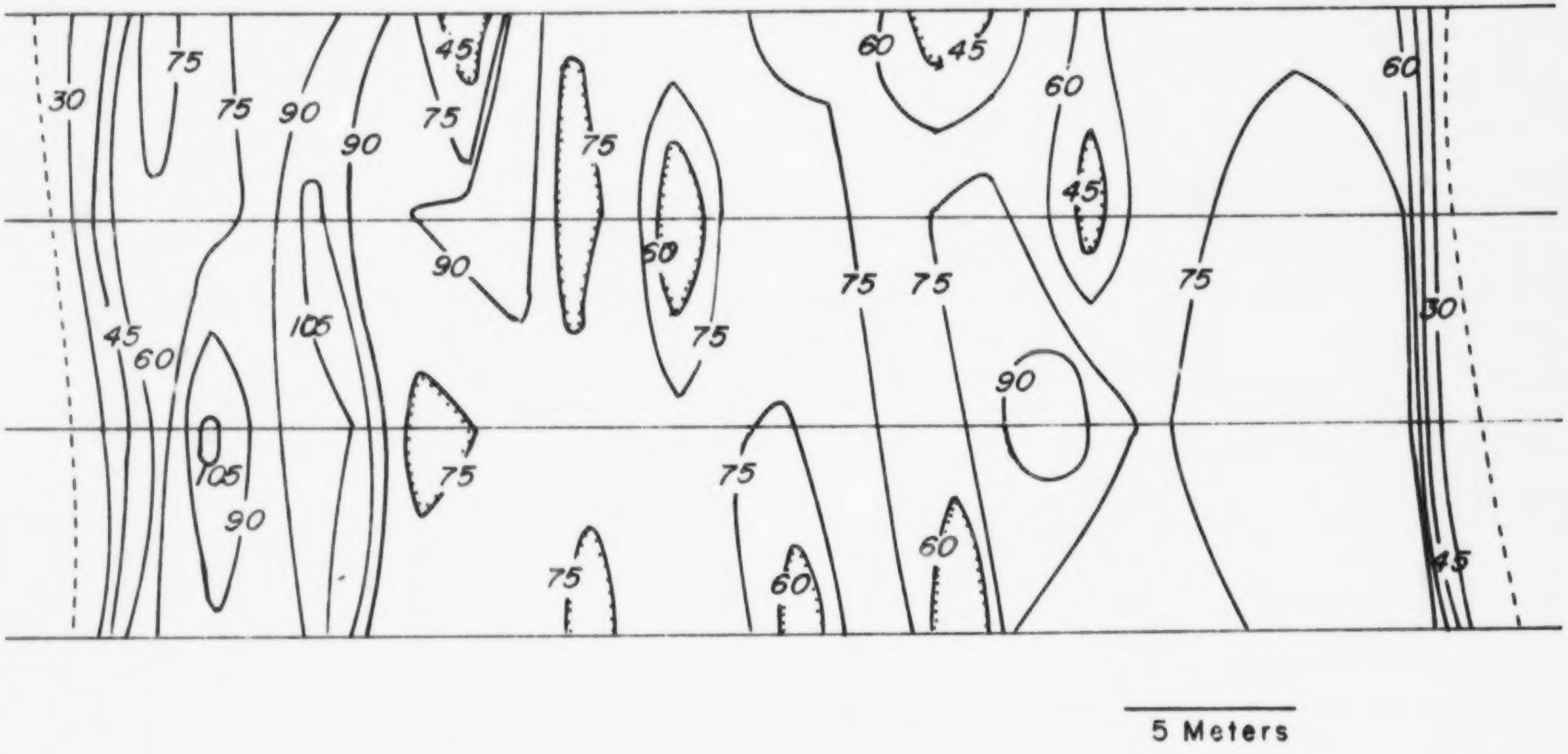


Figure A-4: Velocity Contour Map from the Viall Mapping Section. Velocities in cm./sec. Discharge = 12.0 cms.

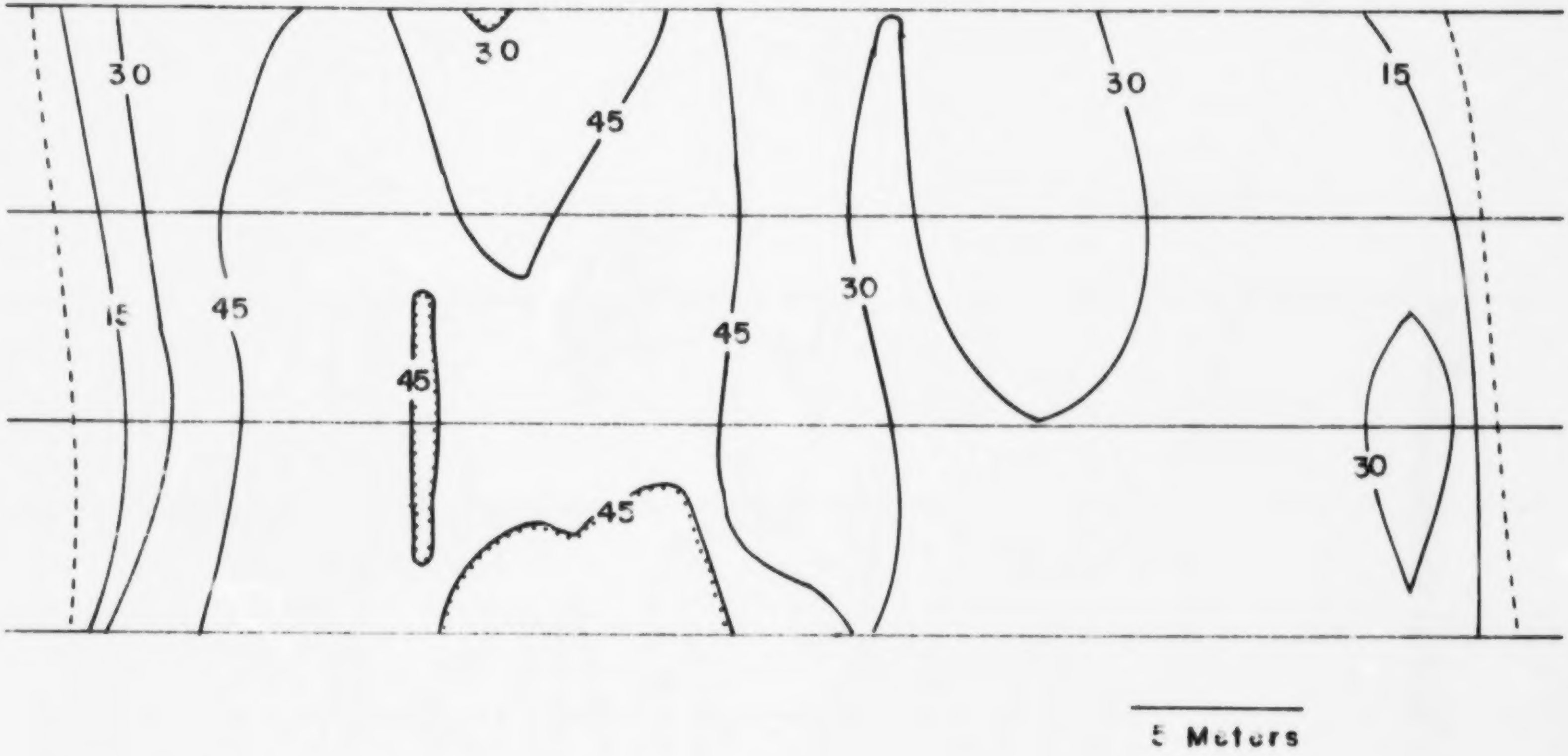


Figure A-5: Depth Contour Map from the Viall Mapping Section. Depths in cm.
Discharge = 10.2 cms.

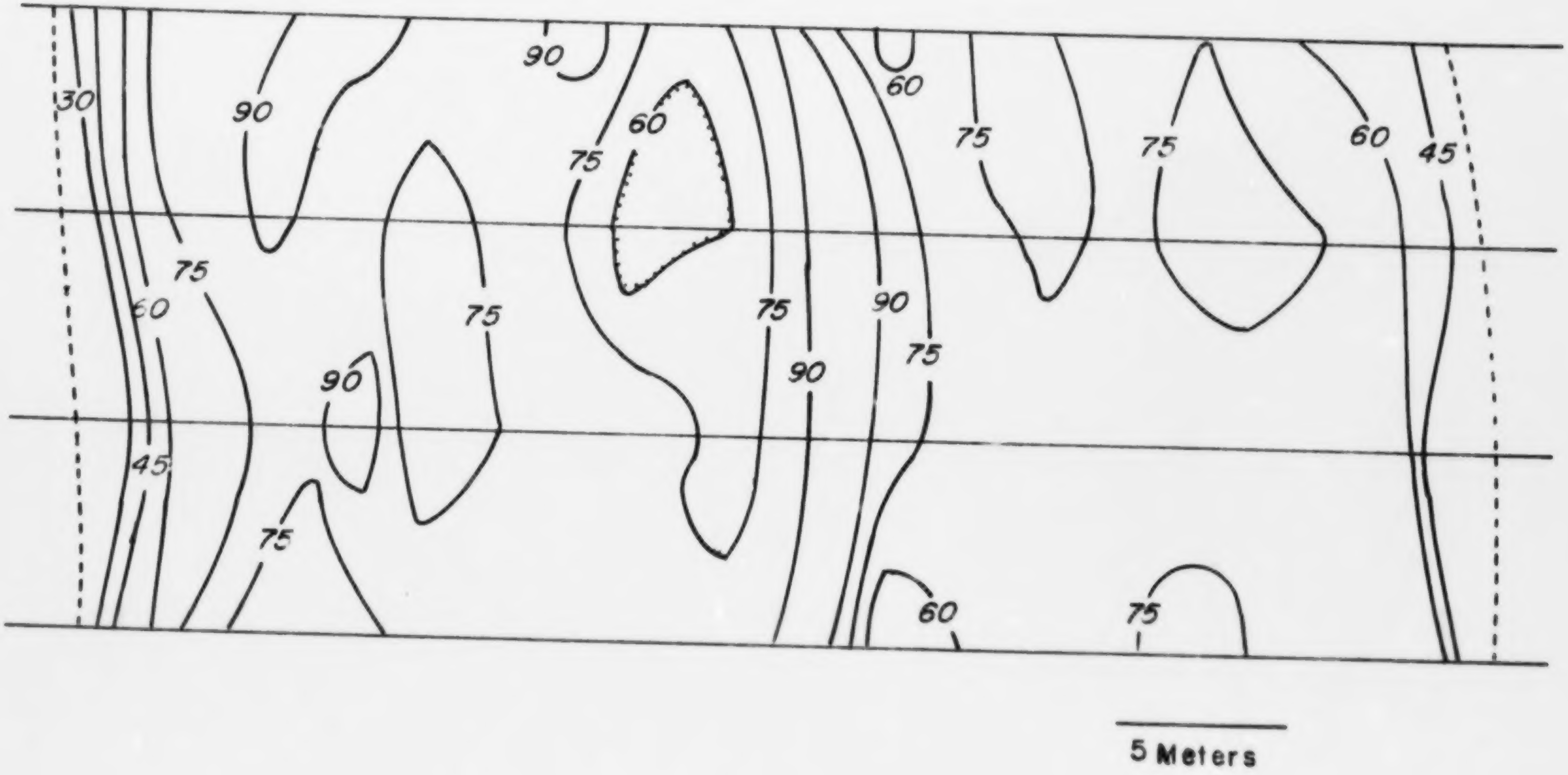


Figure A-6: Velocity Contour Map from the Viall Mapping Section. Velocities in cm./sec. Discharge = 10.2 cms.

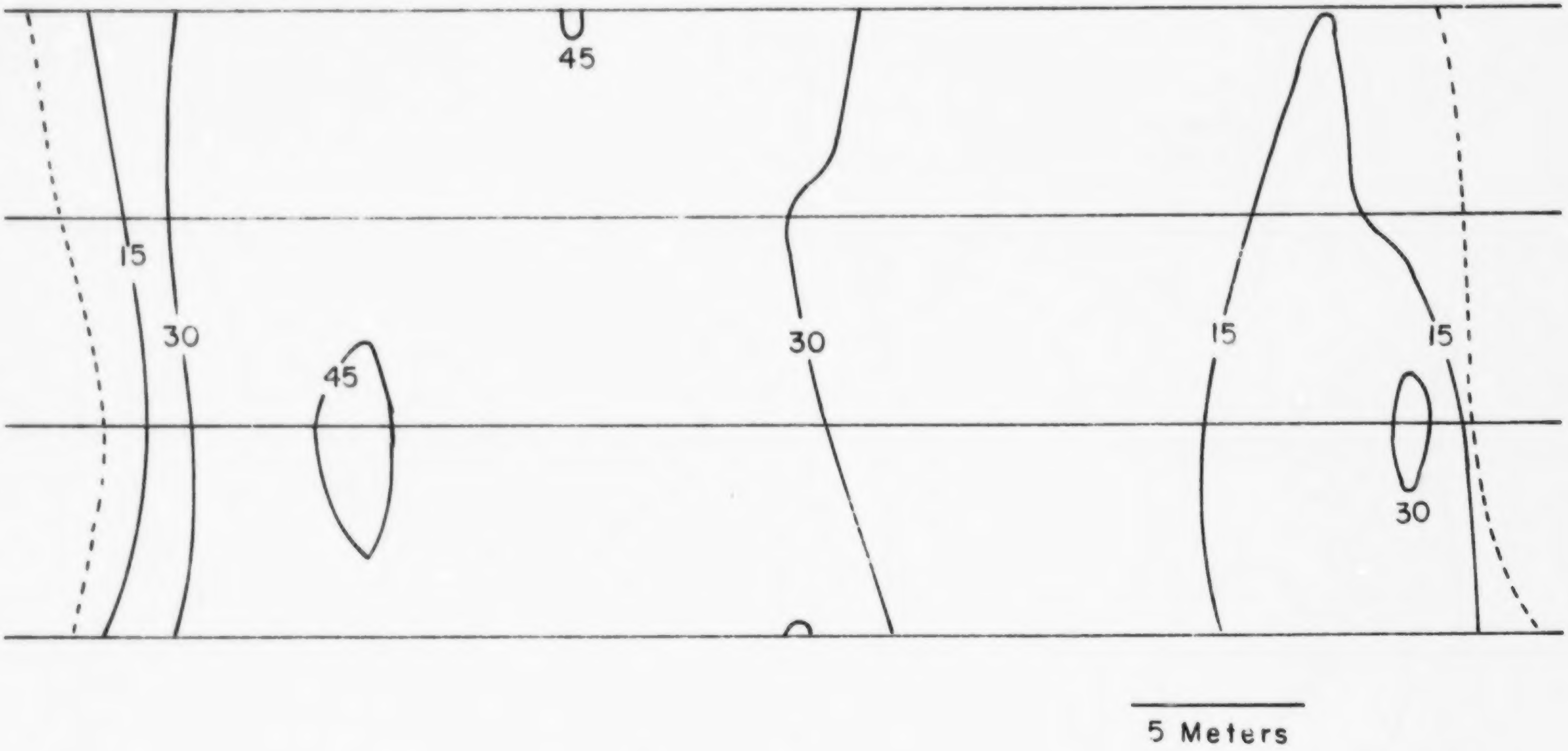


Figure A-7: Depth Contour Map from the Viall Mapping Section. Depths in cm. Discharge = 6.3 cms.

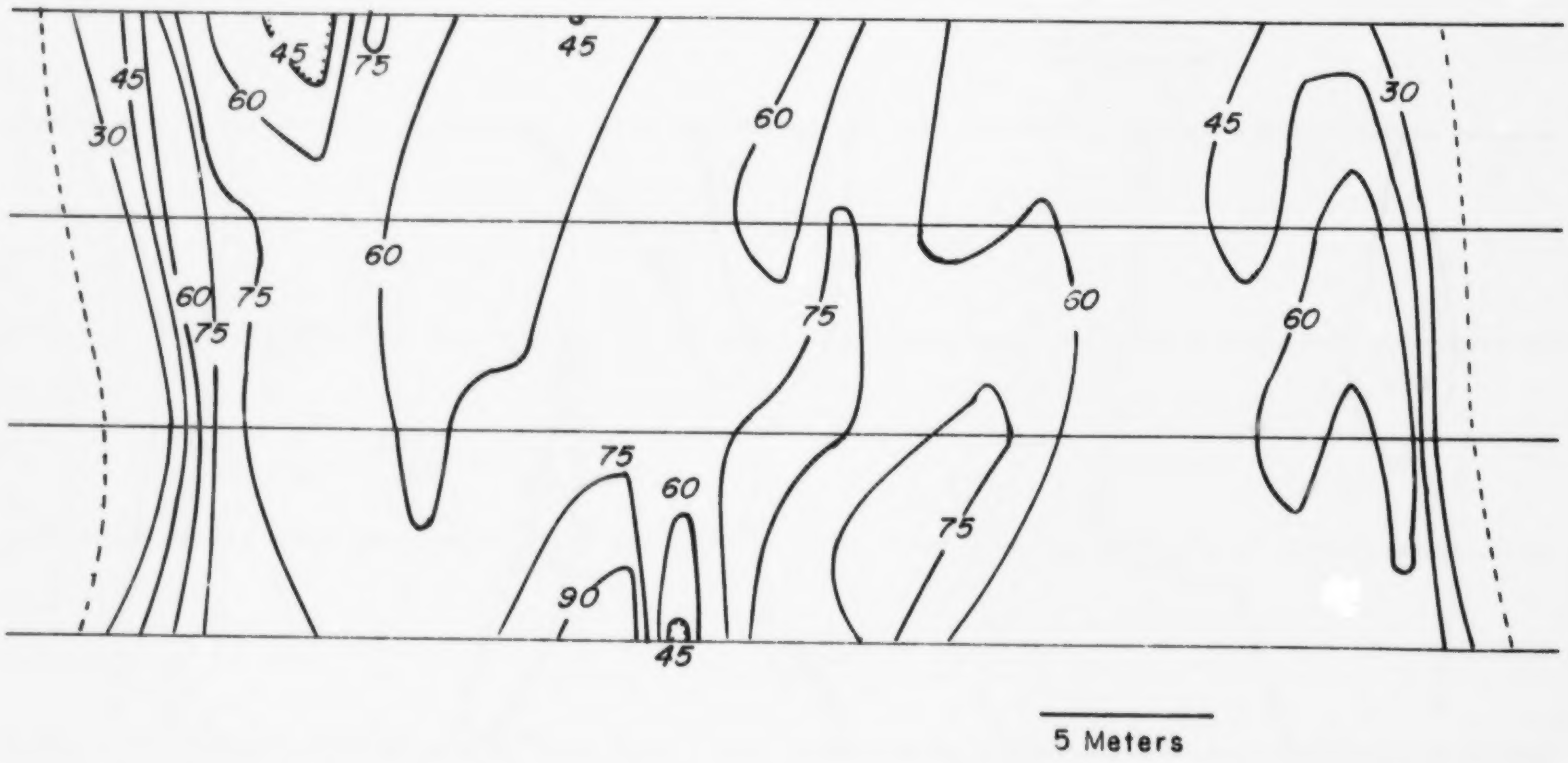


Figure A-8: Velocity Contour Map from the Viall Mapping Section. Velocities in cm./sec. Discharge = 6.3 cms.

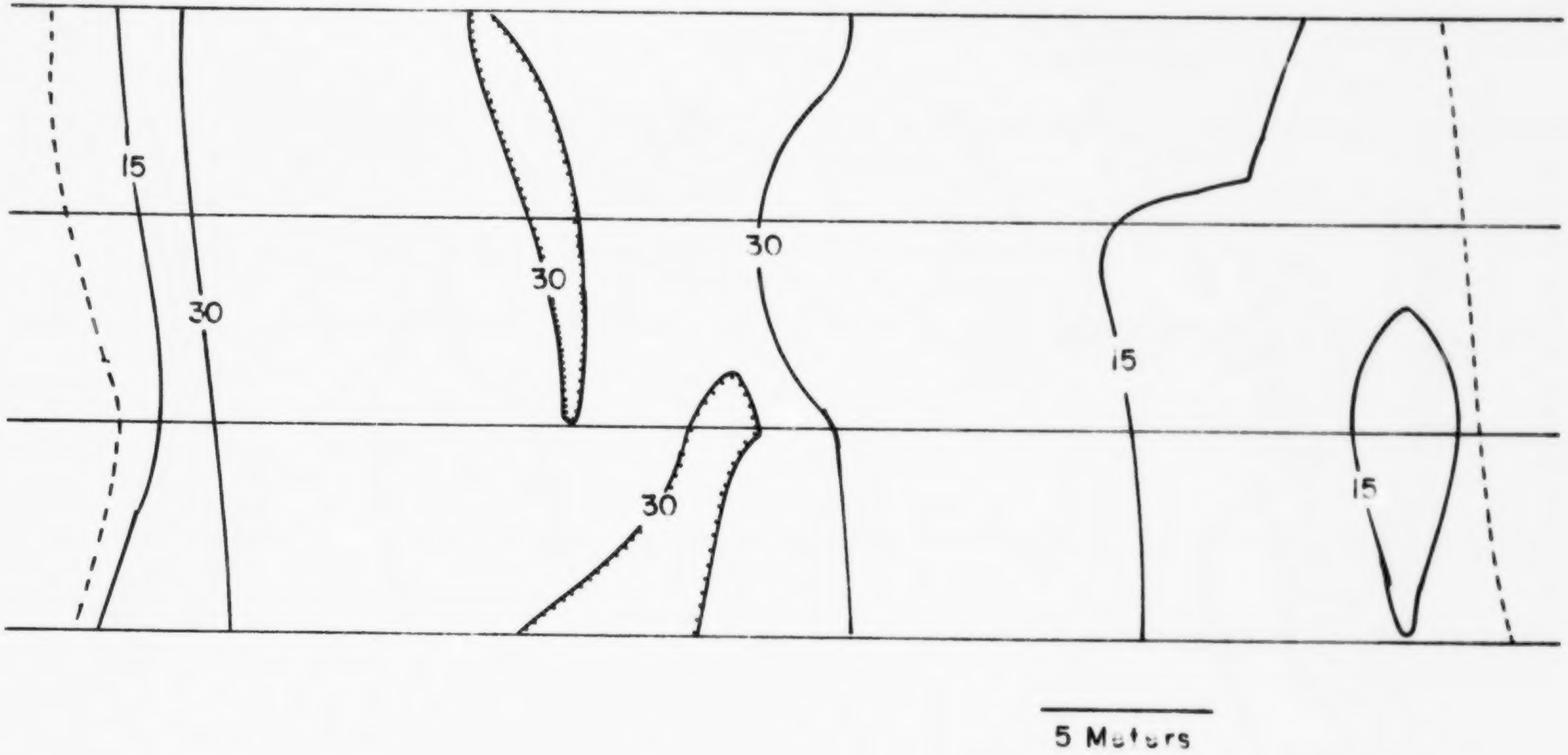


Figure A-9: Depth Contour Map from the Viall Mapping Section. Depths in cm. Discharge = 5.6 cms.

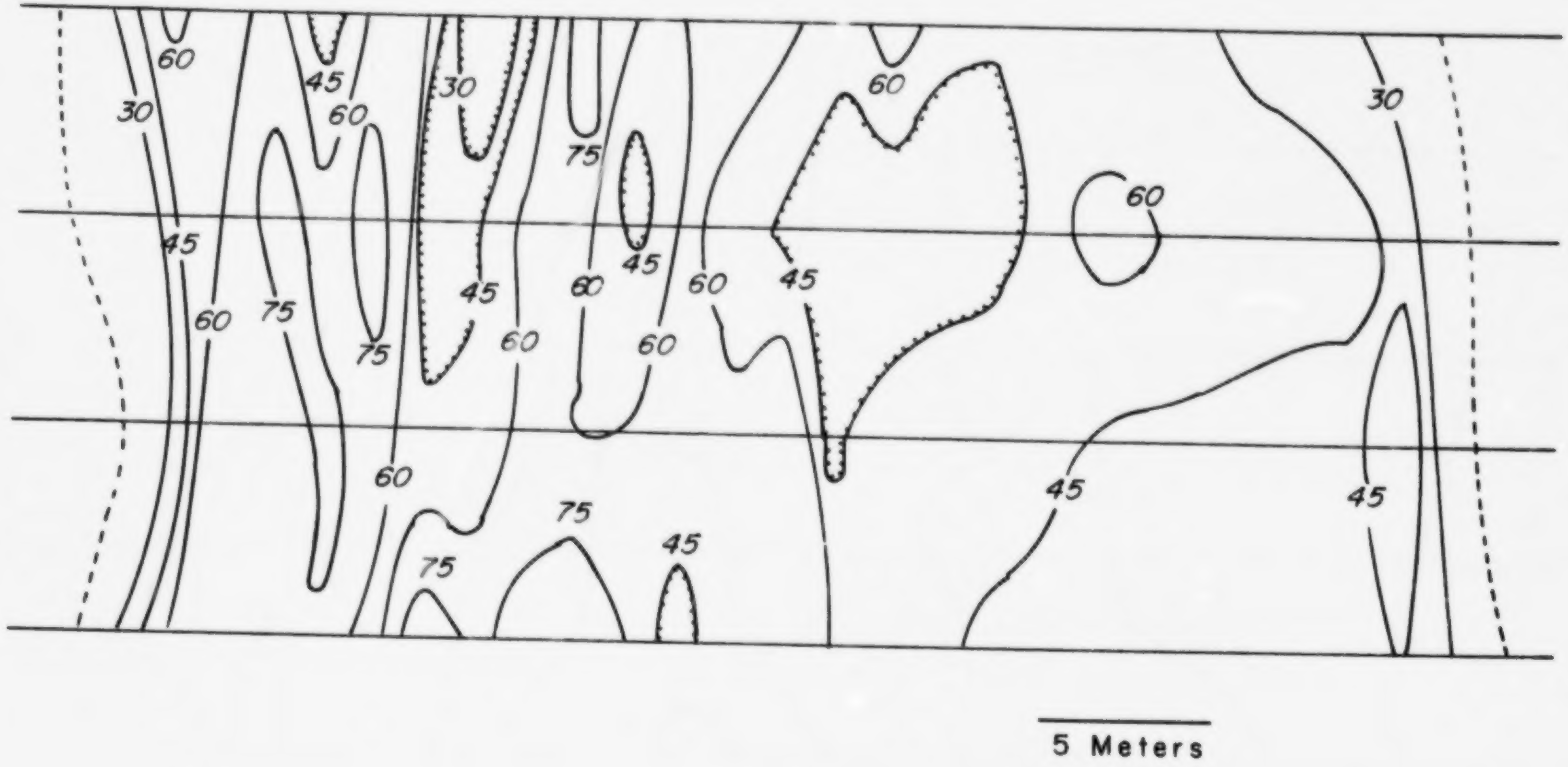


Figure A-10: Velocity Contour Map from the Viall Mapping Section. Velocities in cm./sec. Discharge = 5.6 cms.

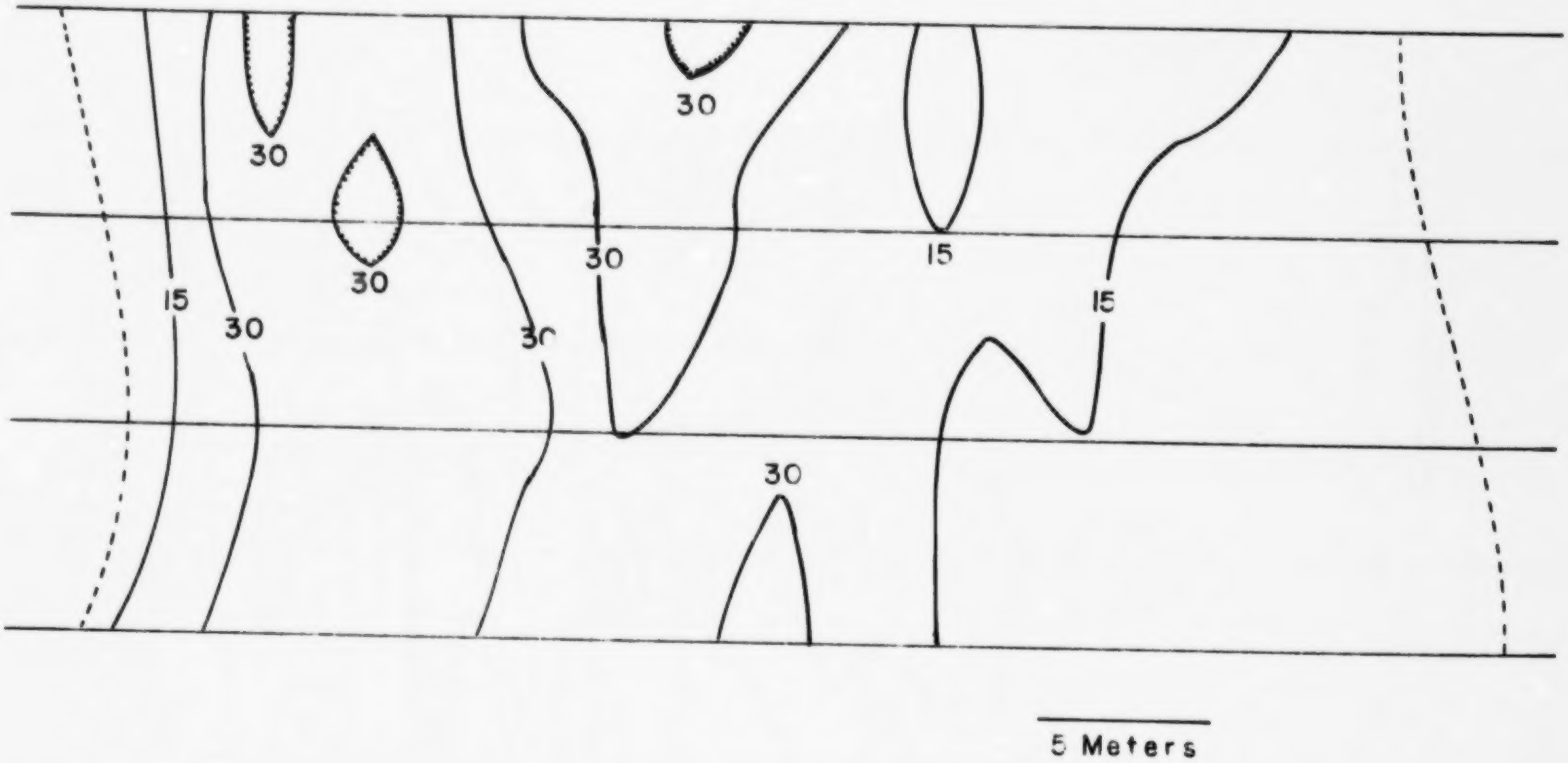


Figure A-11: Depth Contour Map from the Viall Mapping Section. Depths in cm.
Discharge = 4.0 cms.

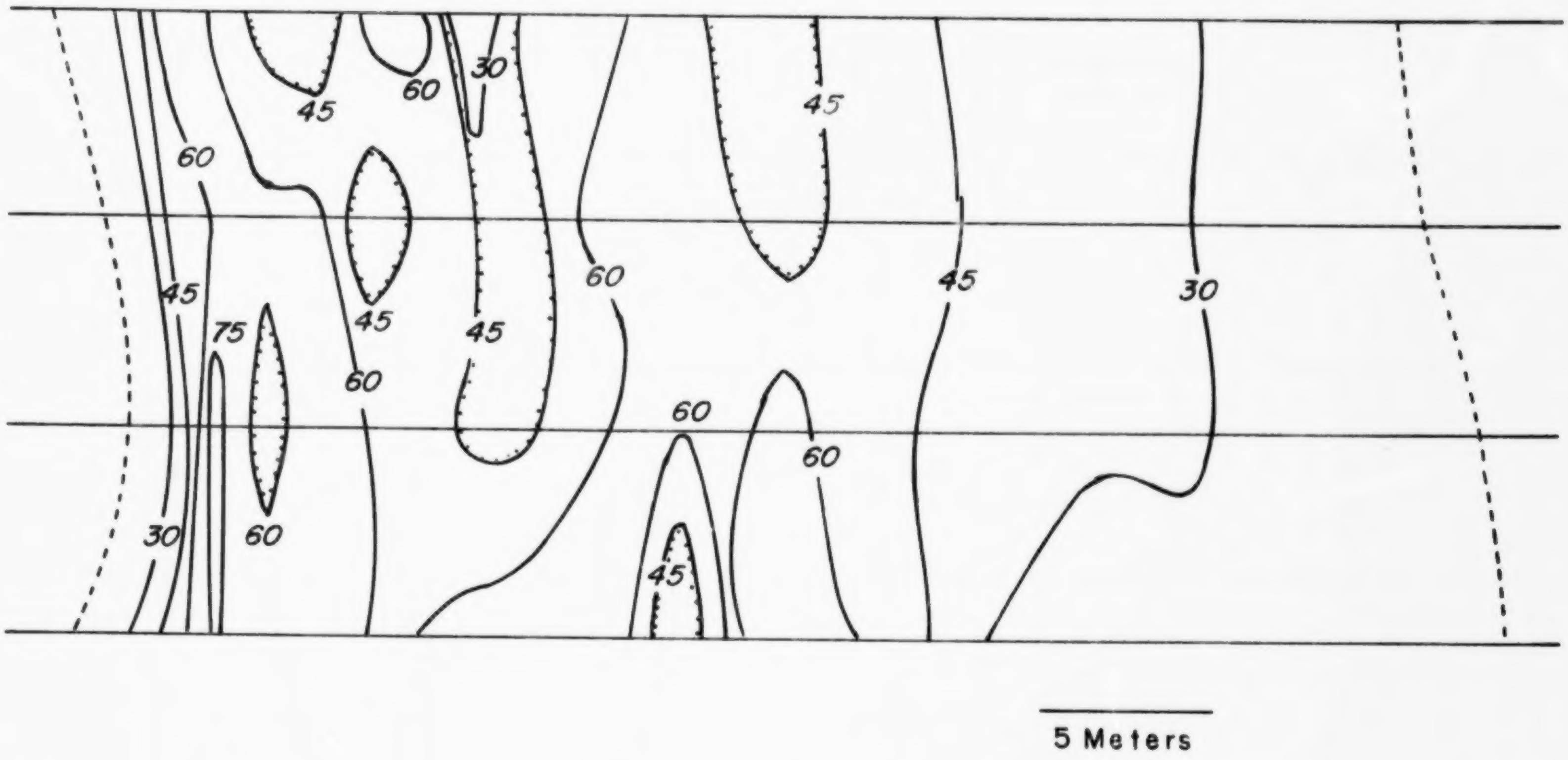


Figure A-12: Velocity Contour Map from the Viall Mapping Section. Velocities in cm./sec. Discharge = 4.0 cms.

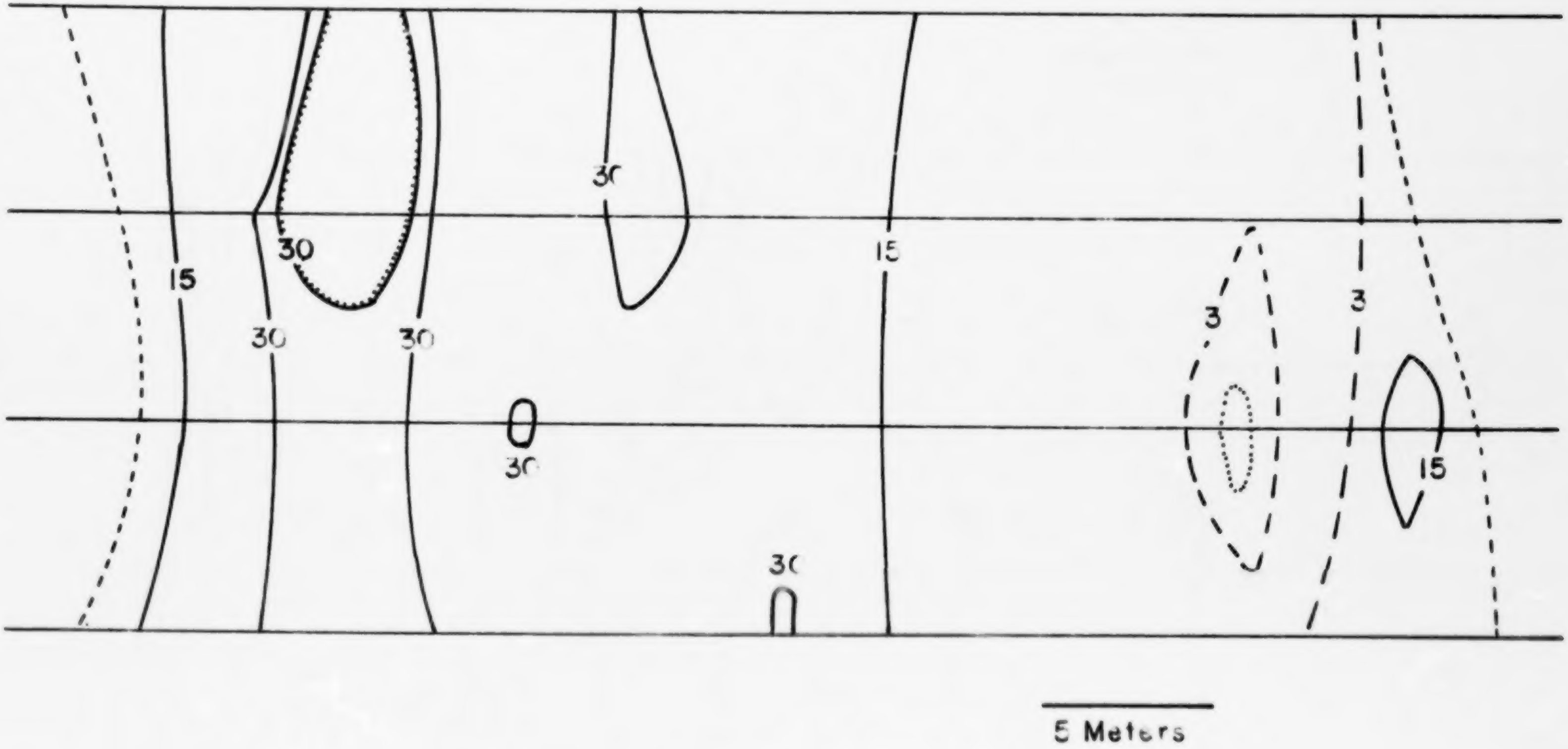


Figure A-13: Depth Contour Map from the Viall Mapping Section. Depths in cm.
Discharge = 2.83 cms.

[redacted]

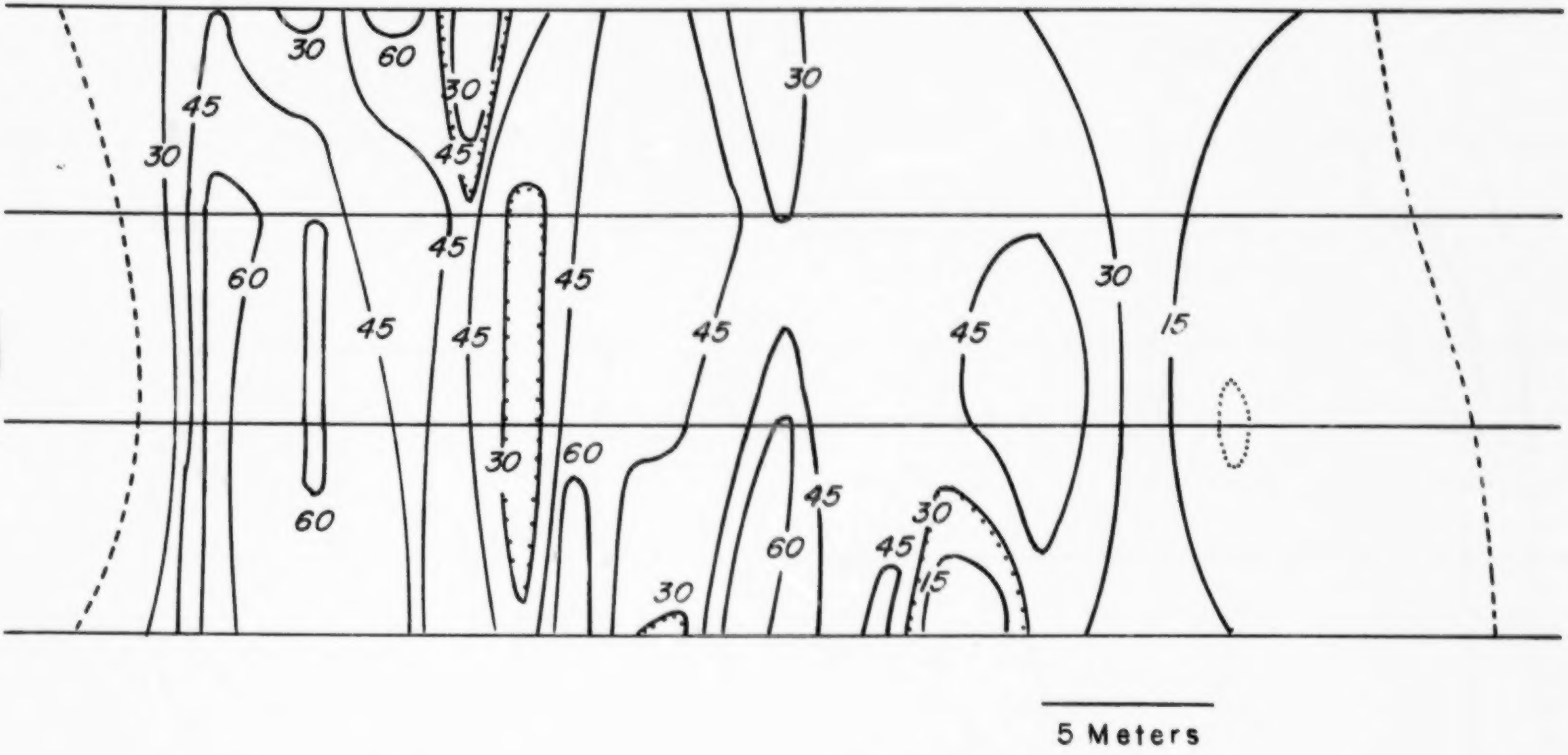


Figure A-14: Velocity Contour Map from the Viall Mapping Section. Velocities in cm./sec. Discharge = 2.83 cms.

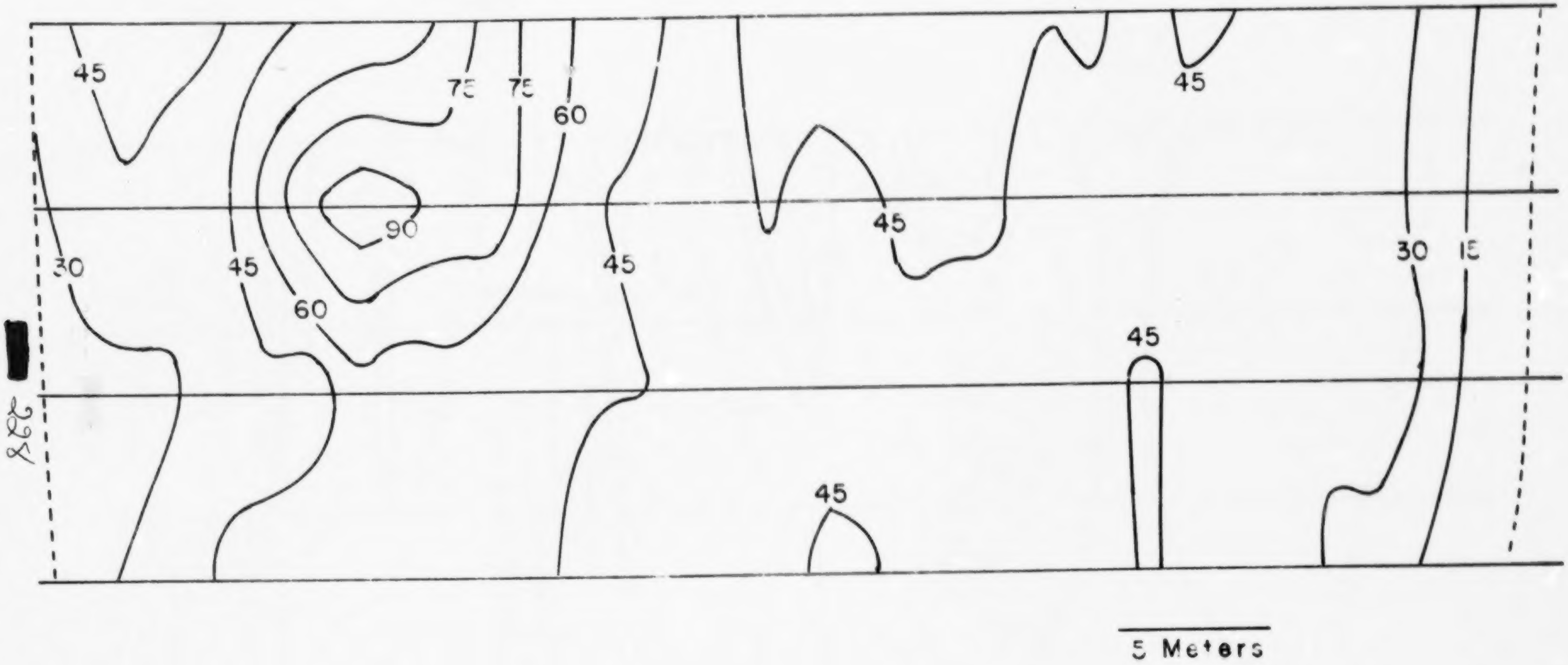


Figure A-15: Depth Contour Map from the Orcutt Mapping Section. Depths in cm.
Discharge = 18.63 cms.

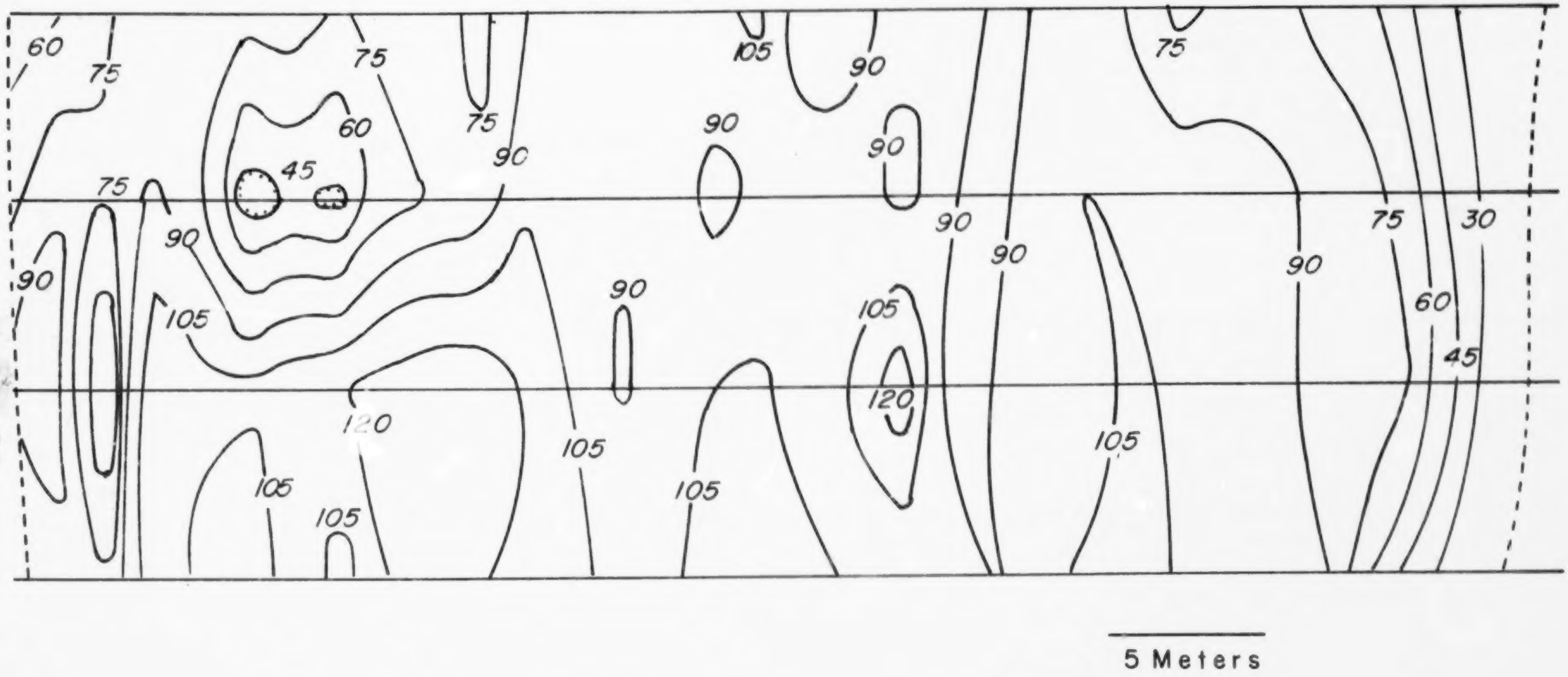


Figure A-16: Velocity Contour Map from the Orcutt Mapping Section. Velocities in cm./sec. Discharge = 18.63 cms.

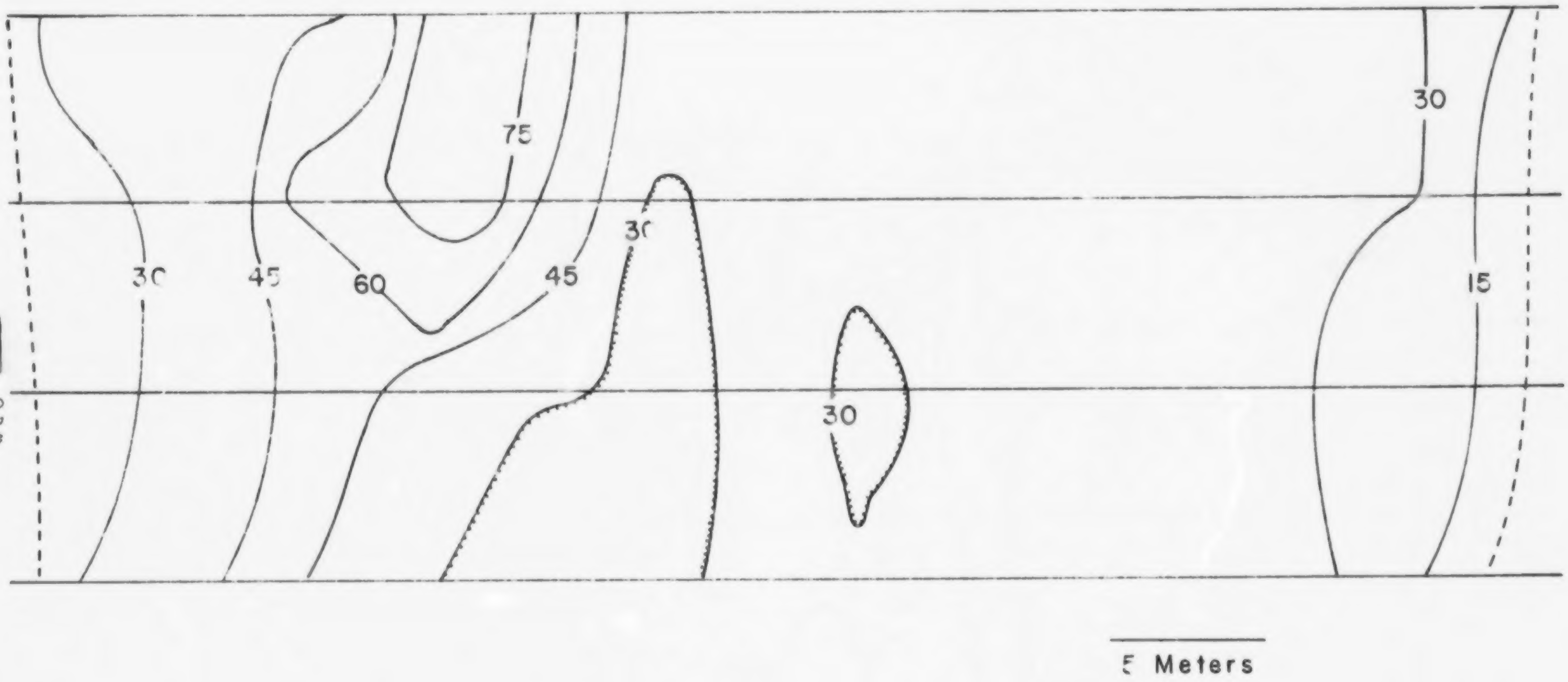


Figure A-17: Depth Contour Map from the Orcutt Mapping Section. Depths in cm. Discharge = 11.14 cms.

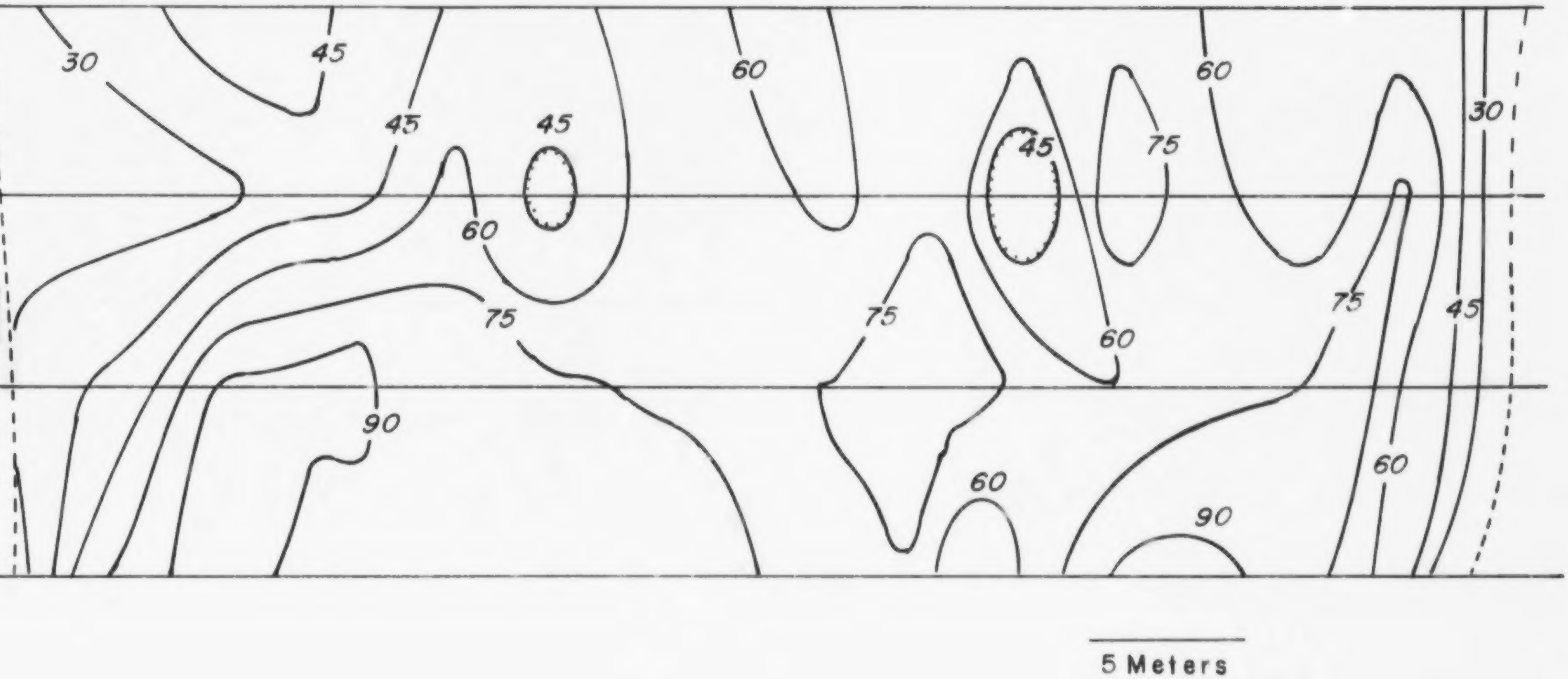


Figure A-18: Velocity Contour Map from the Orcutt Mapping Section. Velocities in cm./sec. Discharge = 11.14 cms.

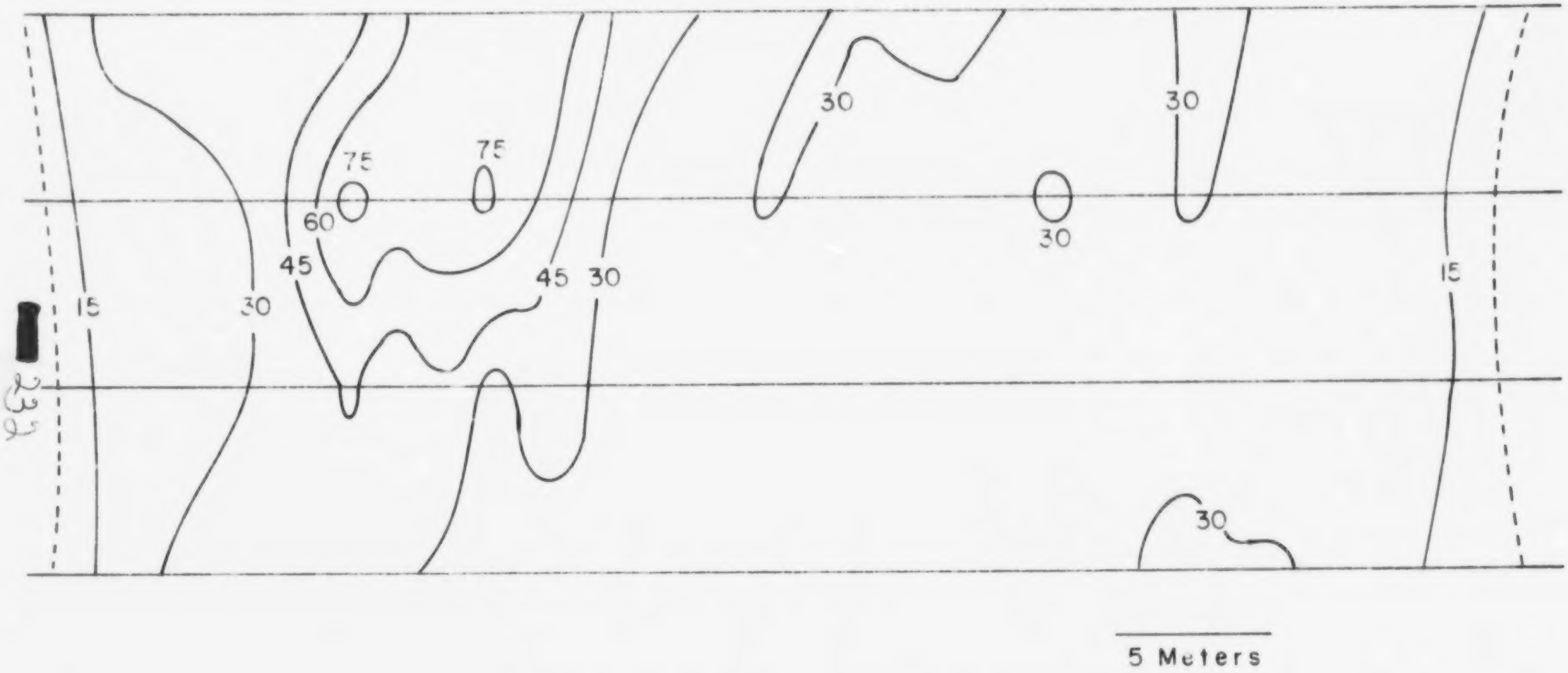


Figure A-19: Depth Contour Map from the Orcutt Mapping Section. Depths in cm. Discharge = 7.58 cms.

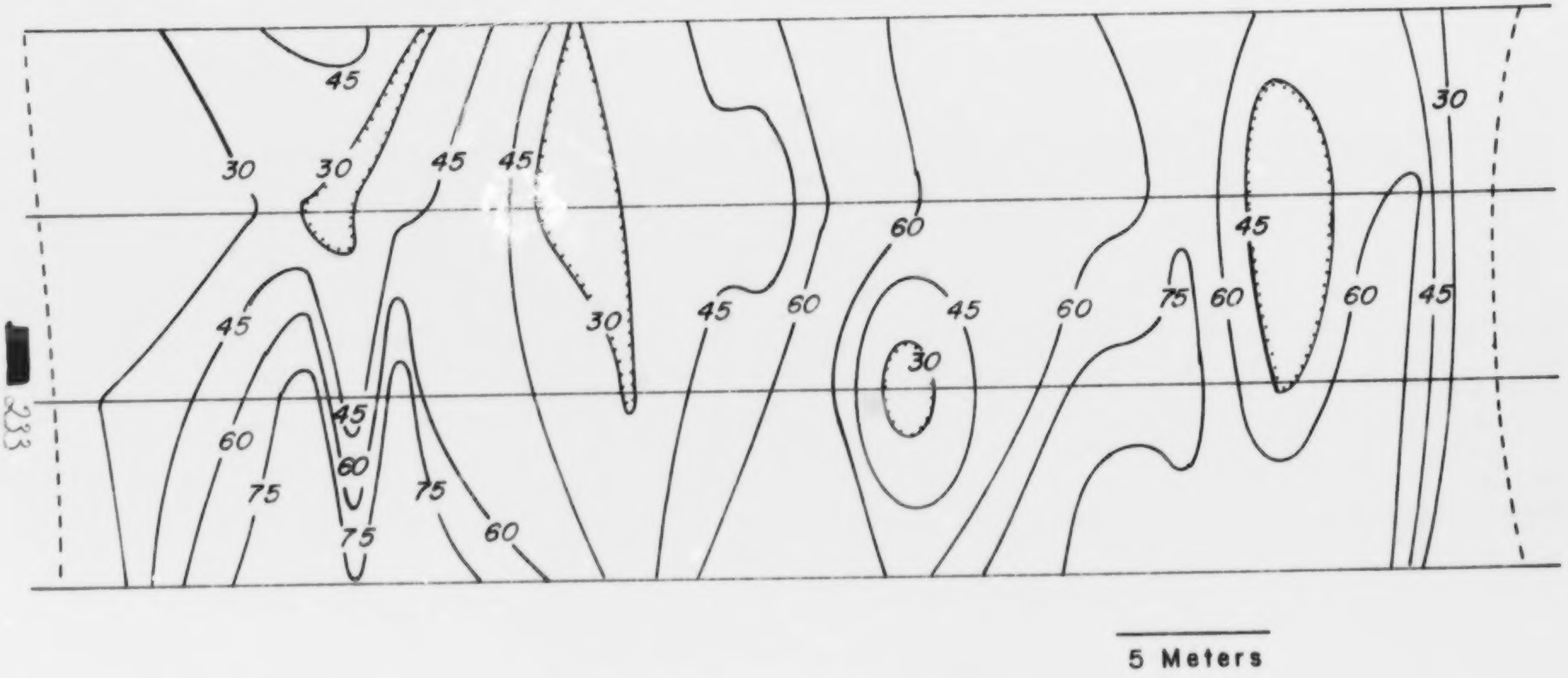


Figure A-20: Velocity Contour Map from the Orcutt Mapping Section. Velocities in cm./sec. Discharge = 7.58 cms.

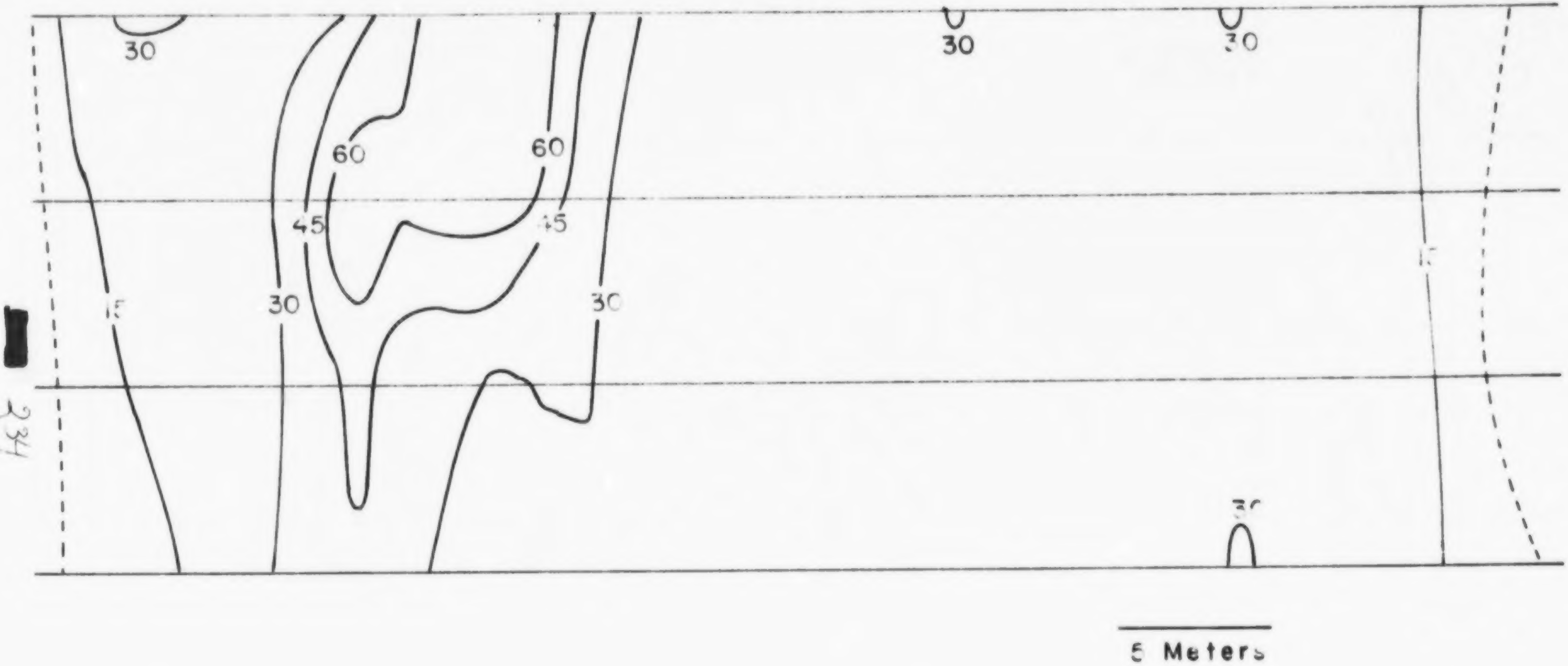


Figure A-21: Depth Contour Map from the Orcutt Mapping Section. Depths in cm.
Discharge = 5.43 cms.

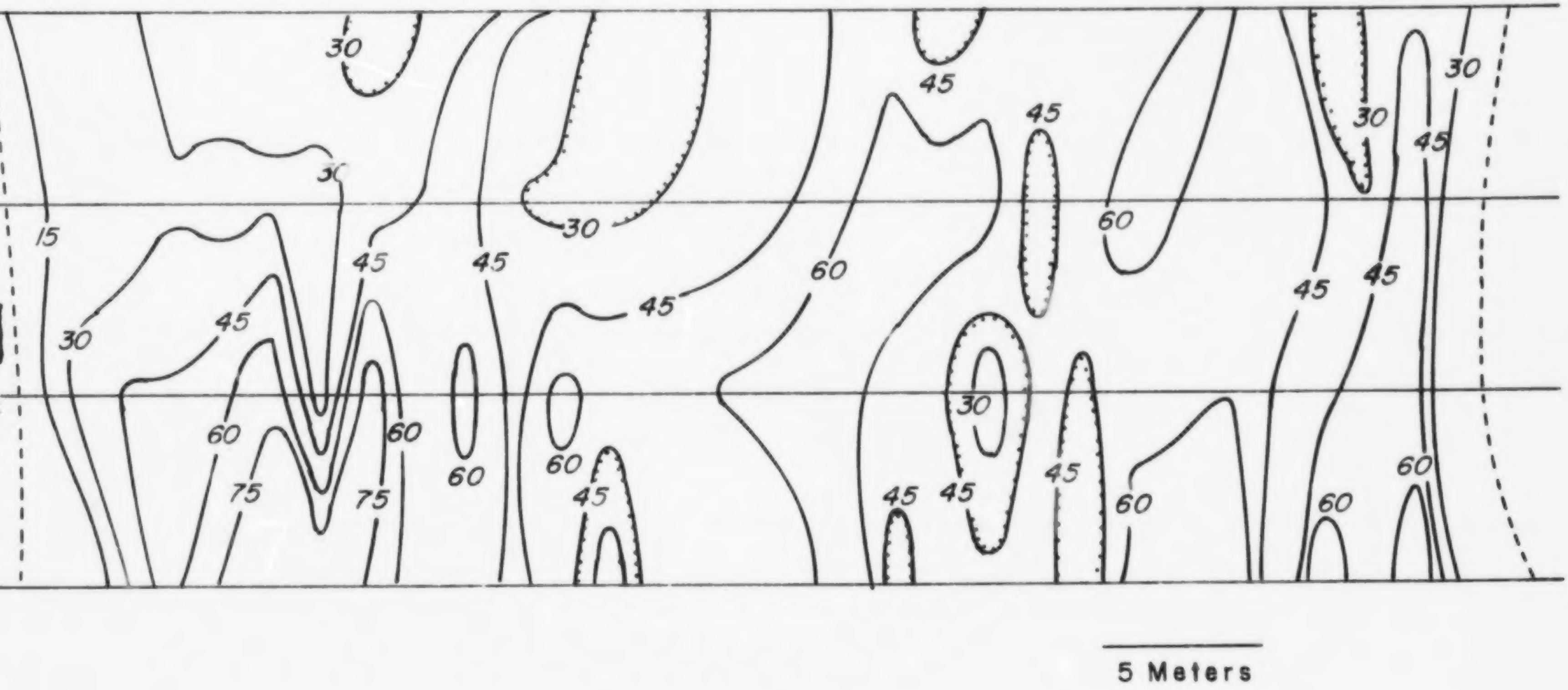


Figure A-22: Velocity Contour Map from the Orcutt Mapping Section. Velocities in cm./sec. Discharge = 5.43 cms.

[redacted]

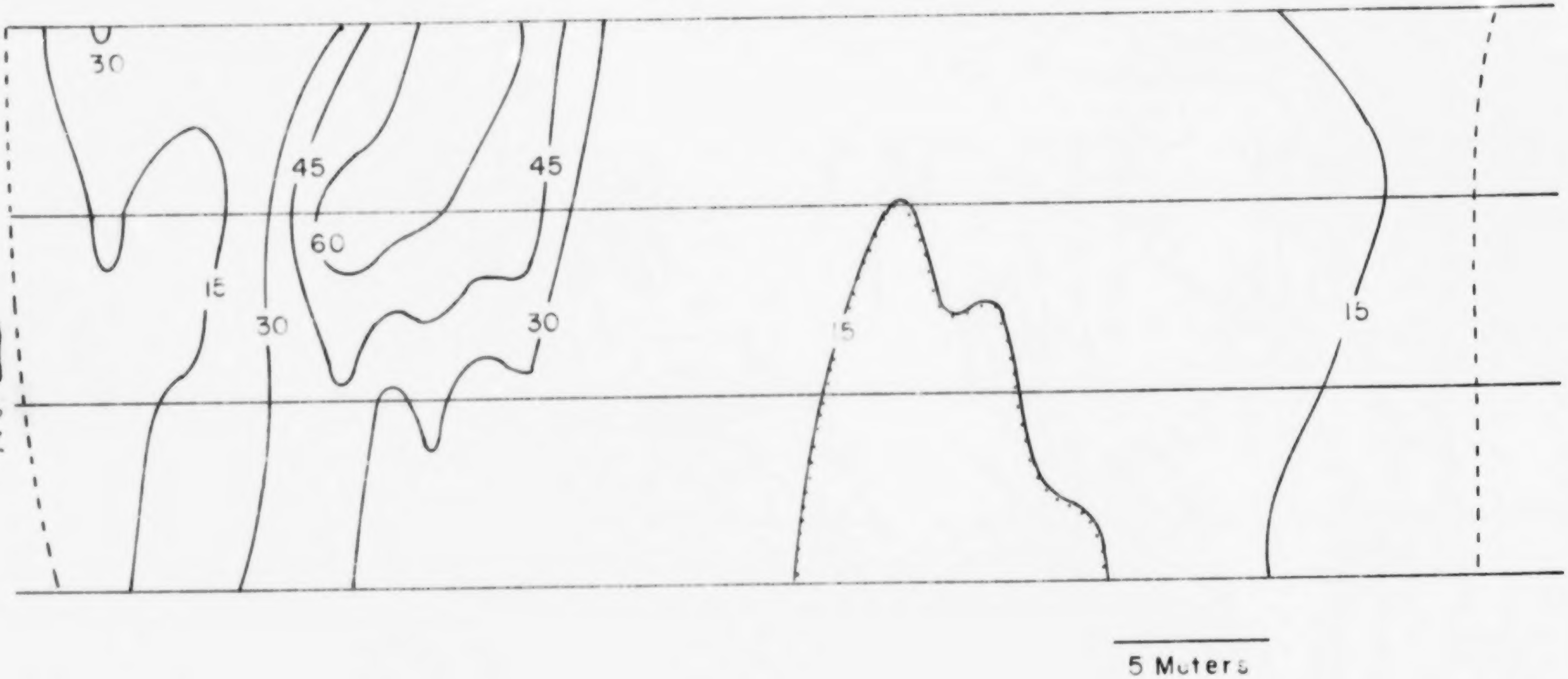


Figure A-23: Depth Contour Map from the Orcutt Mapping Section. Depths in cm. Discharge = 3.85 cms.

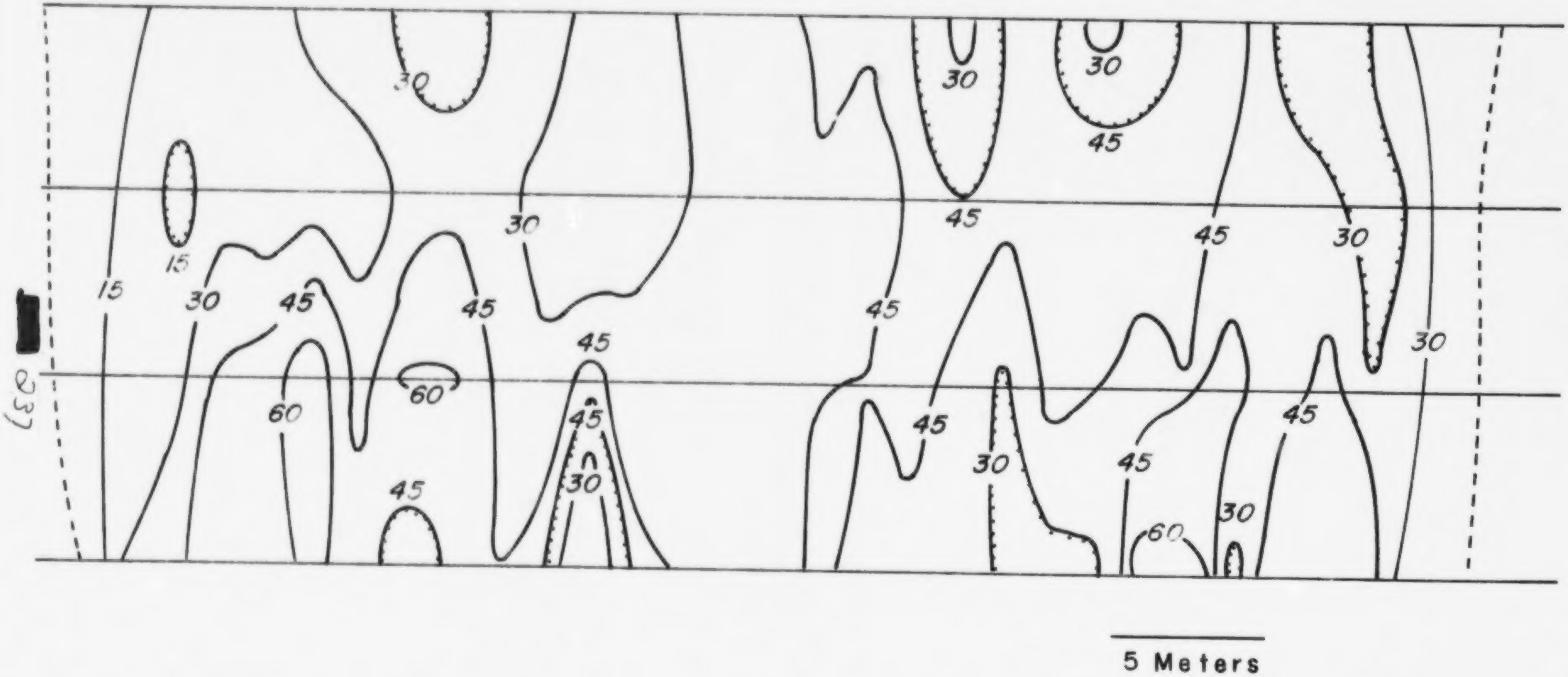


Figure A-24: Velocity Contour Map from the Orcutt Mapping Section. Velocities in cm./sec. Discharge = 3.85 cms.

APPENDIX B

COMPOSITE MAPS

REARING AREAS

1. Direction of flow is from top of page to bottom.

2. These maps indicate areas meeting preferred conditions of depth, velocity, and substrate, for the stonecat.

3. For easier interpretation, depth contours are indicated by vertical typeface. Velocity contours are indicated by slanting typeface.

4. Cross-hatched areas on composite maps indicate areas which do not meet flow criteria for the stonecat. Only those stream areas without cross-hatching meet flow criteria.

5. Dashed lines indicate water's edge, either at stream banks or on exposed bars.

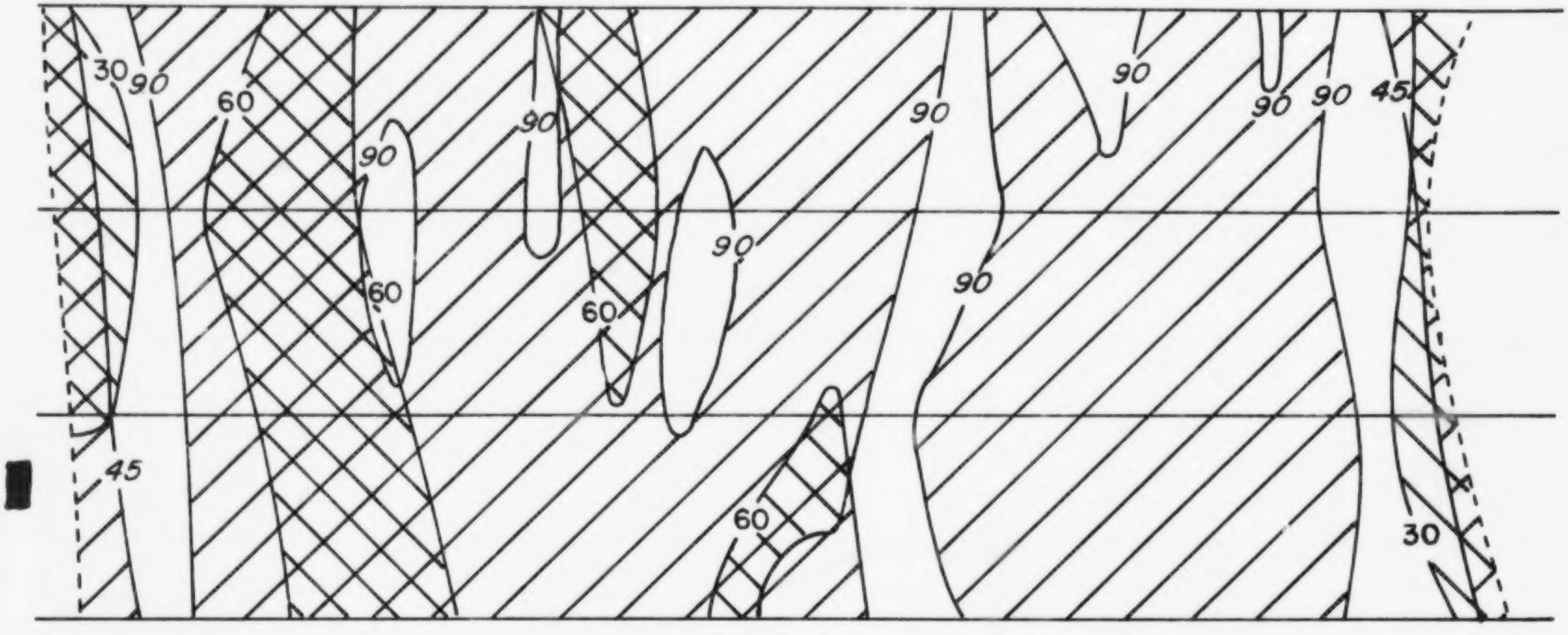

30
90
60
90
60
90
60
90
60
90
90
90
90
90
45
45
60
30
5 Meters
Area not meeting depth criteria
Area not meeting velocity criteria

Figure B-1: Composite Map for the Viall Mapping Section, Showing Areas Meeting Flow Criteria for the Stonecat. Discharge: 19.4 cms.

Area Meeting Criteria: 116 m^2

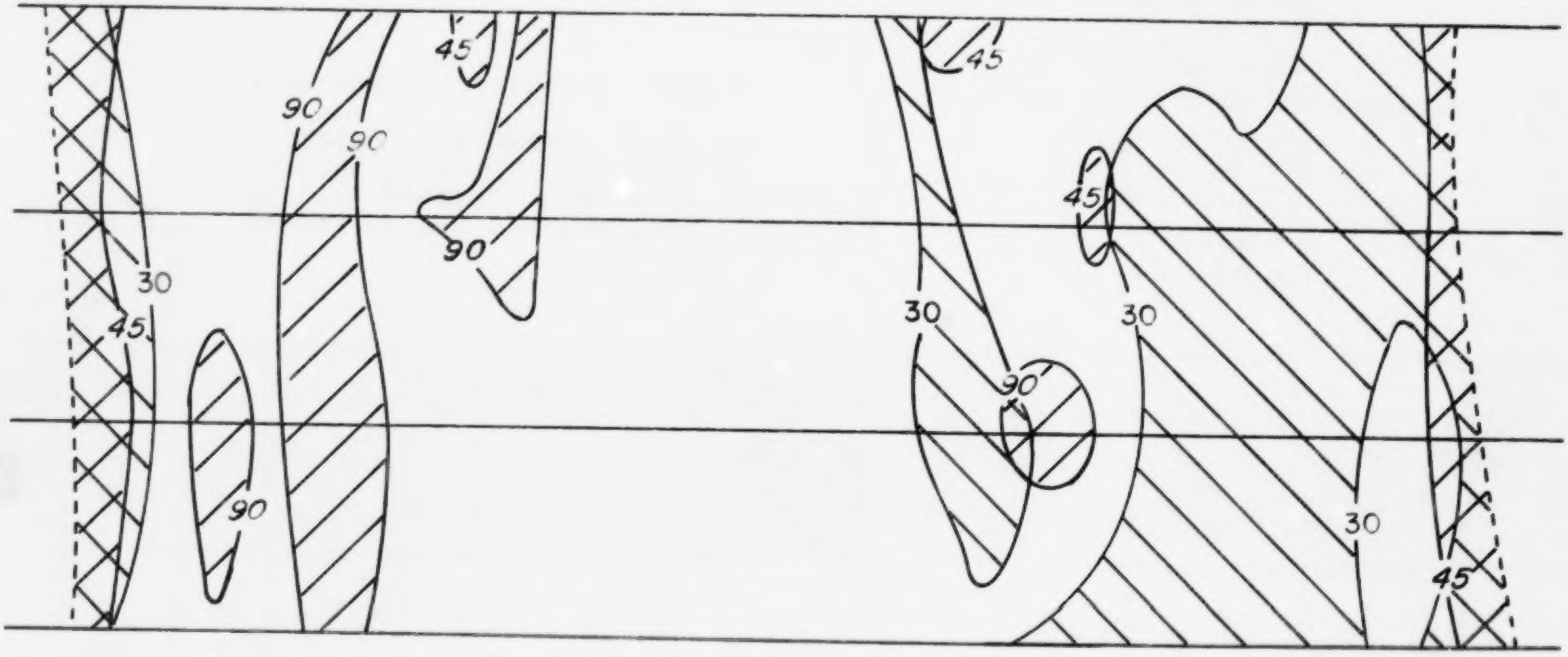


Figure B-2: Composite Map for the Viall Mapping Section, Showing Areas Meeting Flow Criteria for the Stonecat. Discharge: 12.0 cms.

Area Meeting Criteria: 425 m^2

5 Meters

▧ Area not meeting depth criteria

▨ Area not meeting velocity criteria

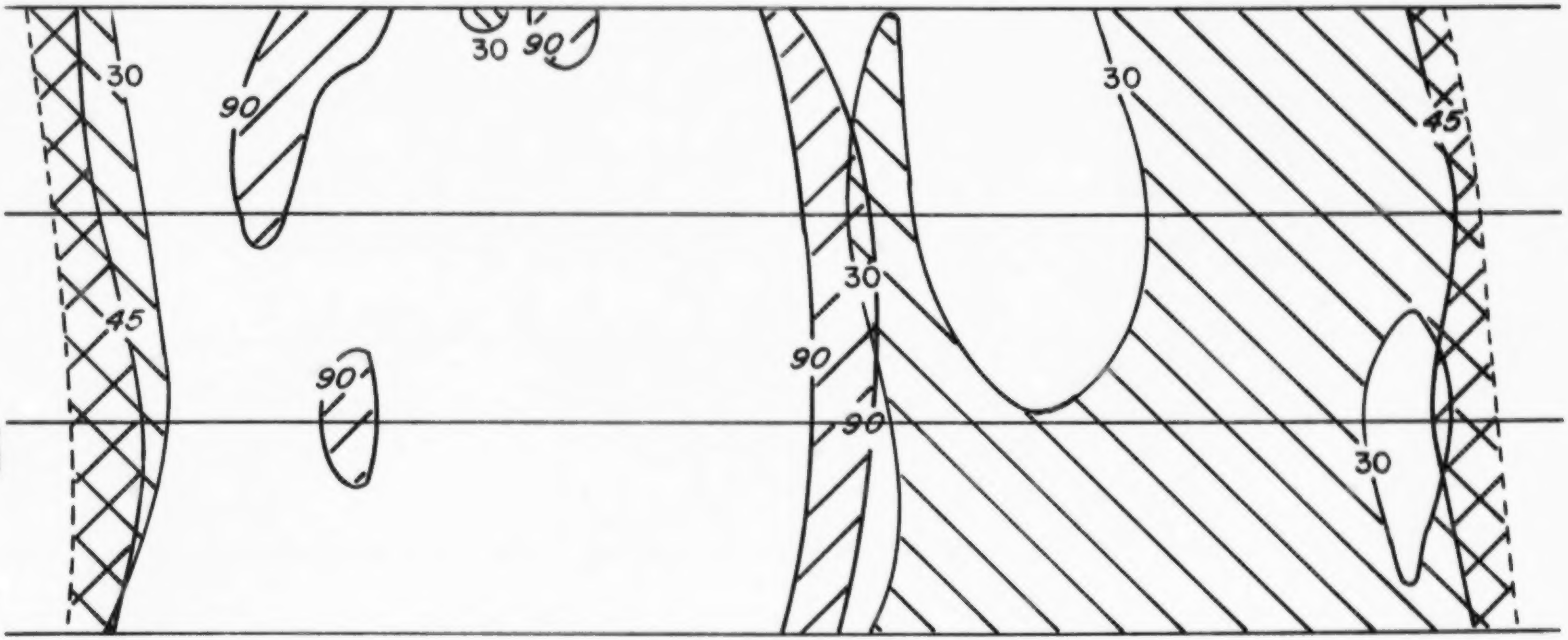


Figure B-3: Composite Map for the Viall Mapping Section, Showing Areas Meeting Flow Criteria for the Stonecat. Discharge: 10.2 cms.

Area Meeting Criteria: 401 m^2

5 Meters

▧ Area not meeting depth criteria

▨ Area not meeting velocity criteria

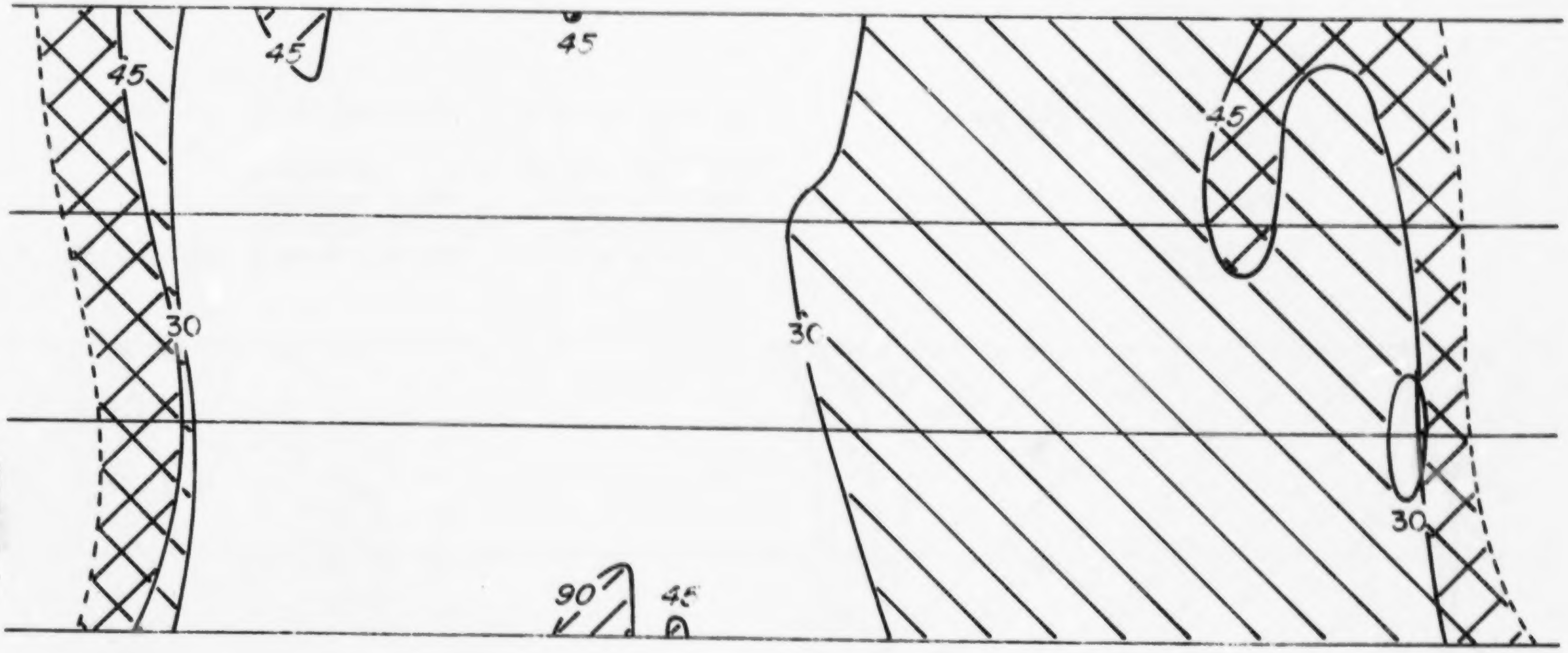


Figure B-4: Composite Map for the Viall Mapping Section, Showing Areas Meeting Flow Criteria for the Stonecat. Discharge: 6.30 cms.

Area Meeting Criteria: 335 m^2

5 Meters

▨ Area not meeting depth criteria

▨ Area not meeting velocity criteria

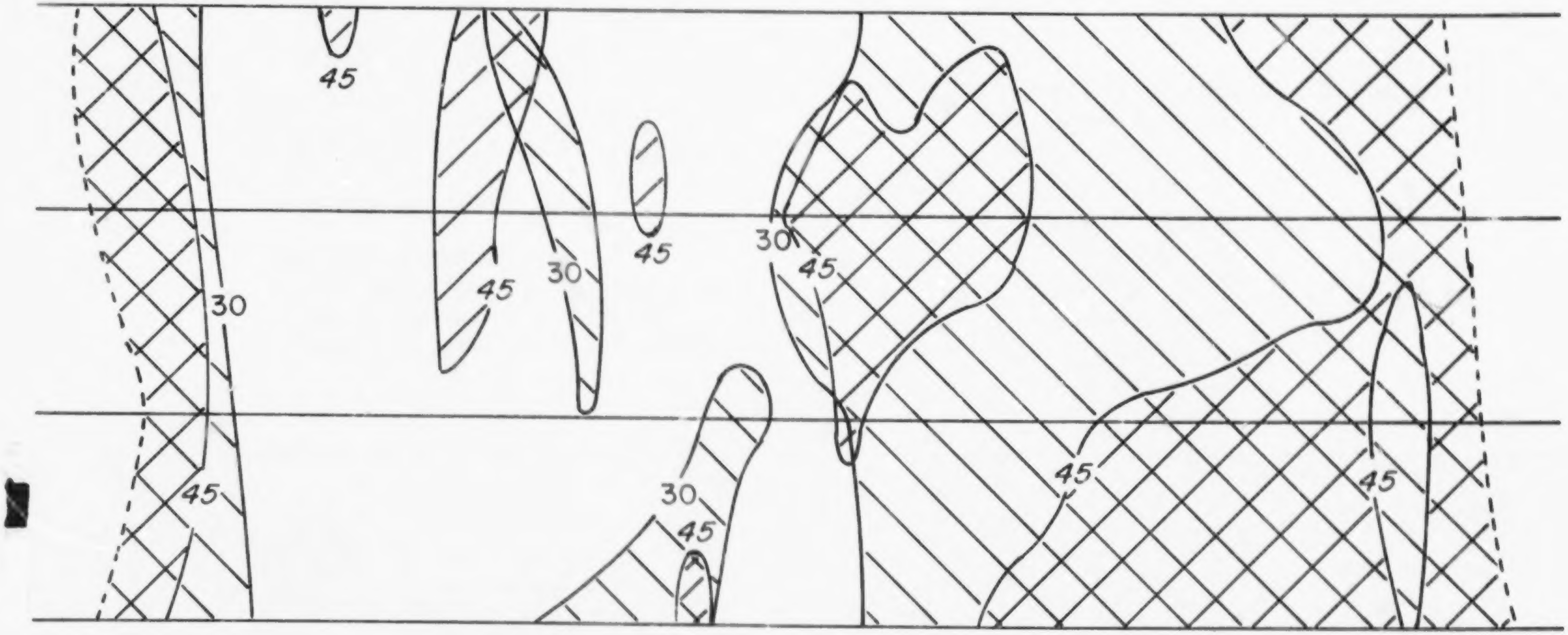


Figure B-5: Composite Map for the Viall Mapping Section, Showing Areas Meeting Flow Criteria for the Stonecat.

Discharge: 5.58 cms.

Area Meeting Criteria: 264 m^2

5 Meters

▧ Area not meeting depth criteria

▨ Area not meeting velocity criteria

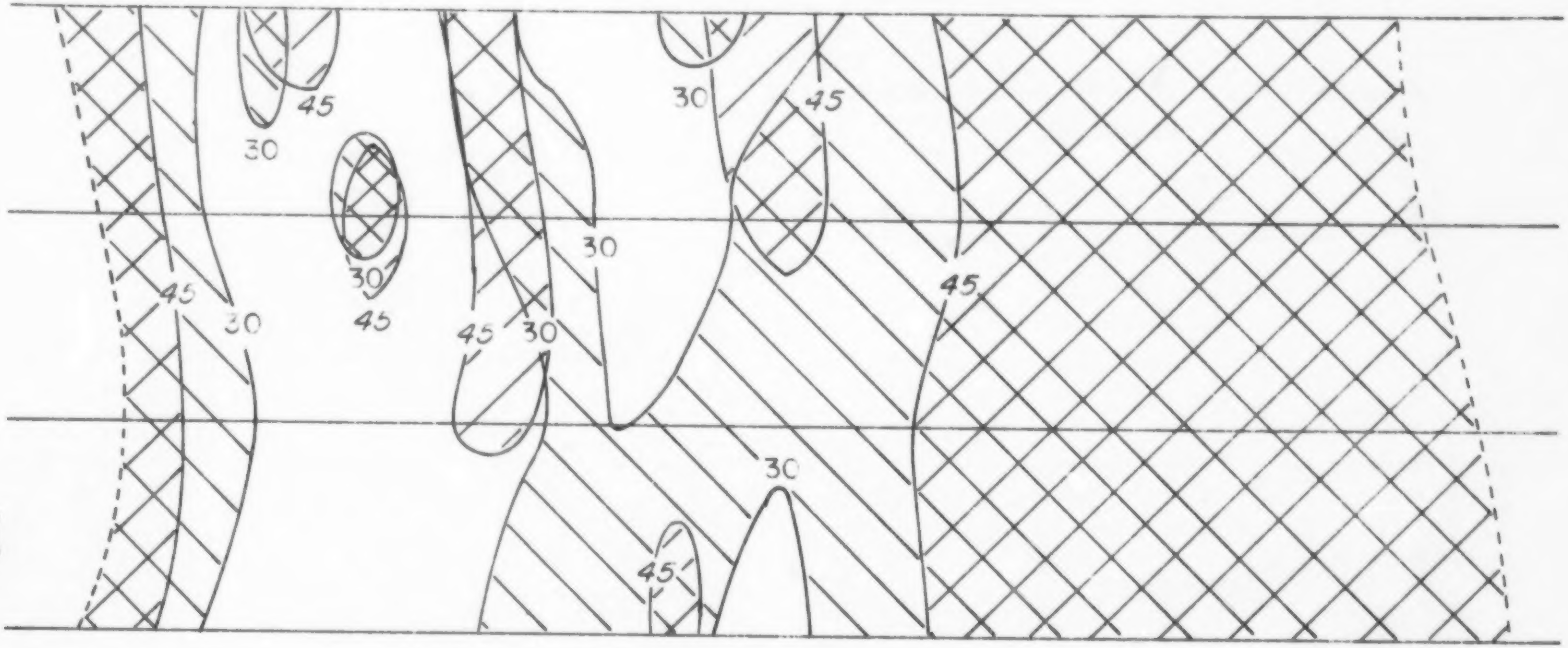


Figure B-6: Composite Map for the Viall Mapping Section, Showing Areas Meeting Flow Criteria for the Stonecat.

Discharge: 4.02 cms.

Area Meeting Criteria: 171 m^2

5 Meters

▧ Area not meeting depth criteria

▨ Area not meeting velocity criteria

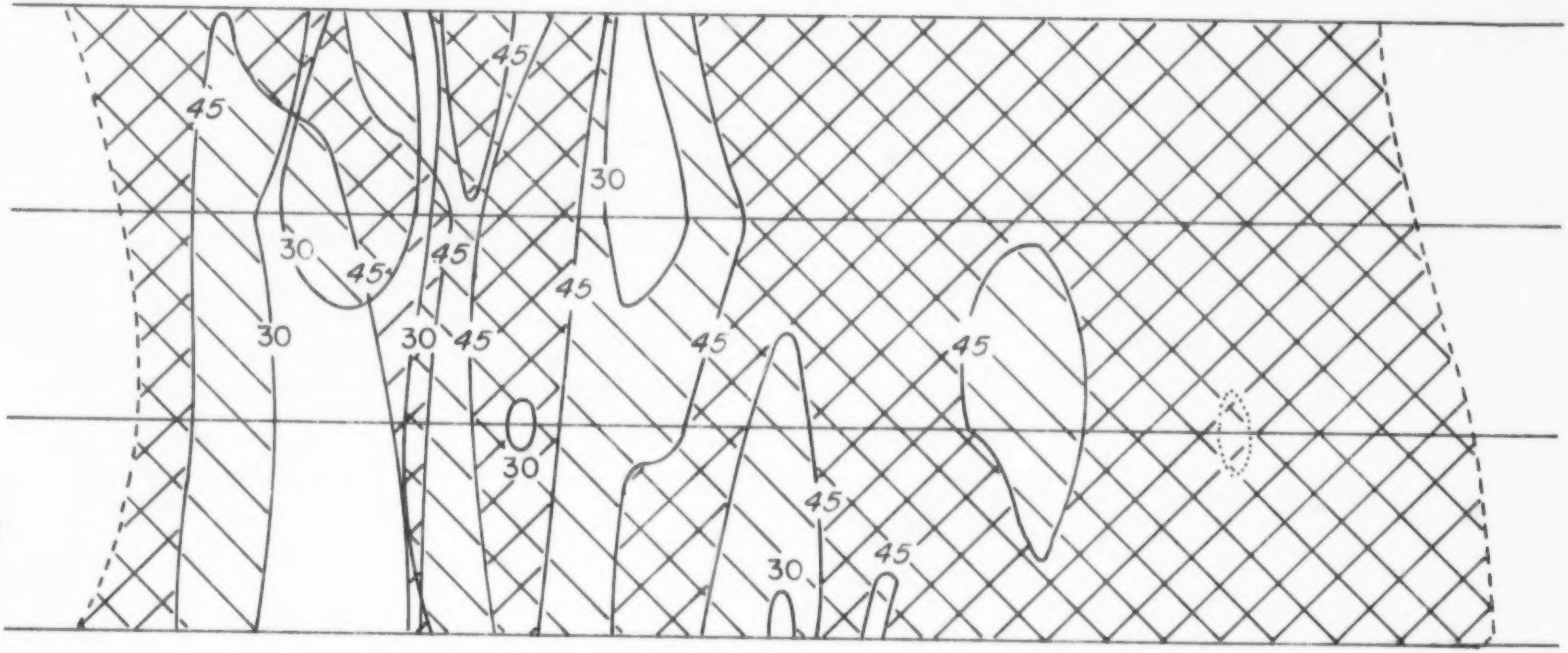


Figure B-7: Composite Map for the Viall Mapping Section, Showing Areas Meeting Flow Criteria for the Stonecat.

Discharge: 2.83 cms.

Area Meeting Criteria: 54 m^2

5 Meters

▧ Area not meeting depth criteria

▨ Area not meeting velocity criteria

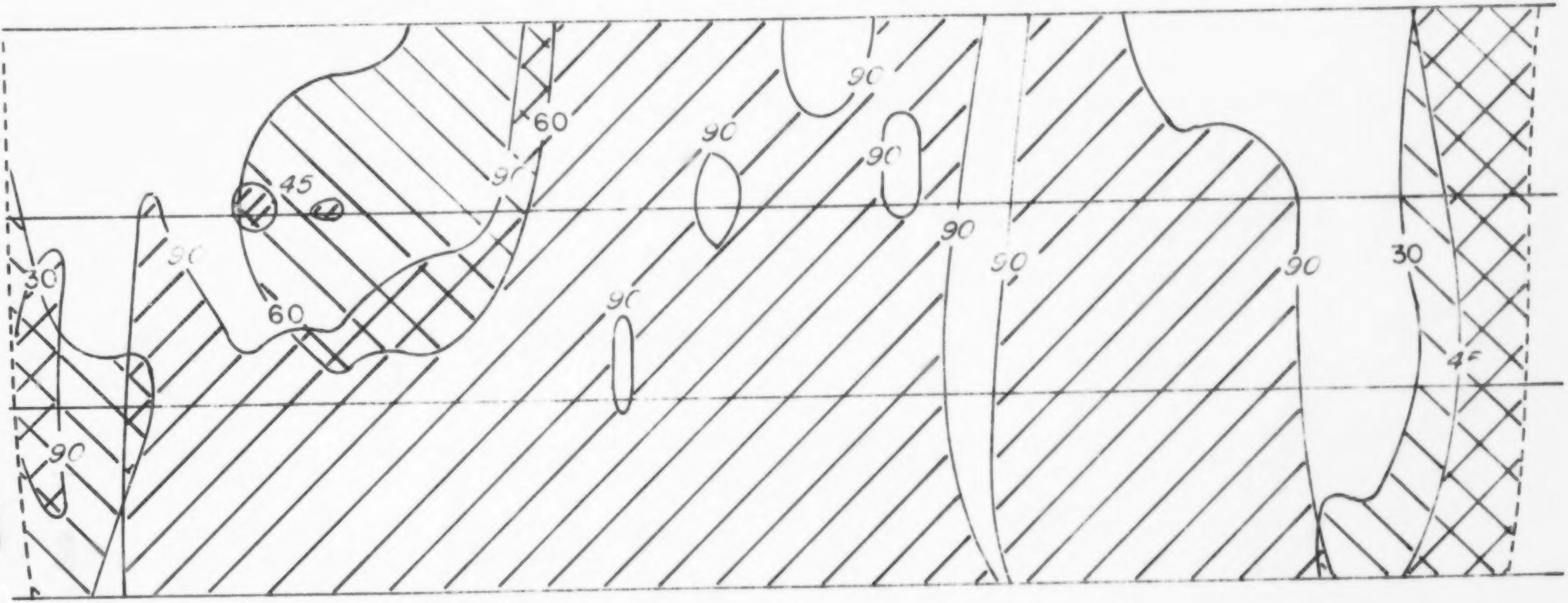


Figure B-8: Composite Map for the Orcutt Mapping Section. Showing Areas Meeting Flow Criteria for the Stonecat.

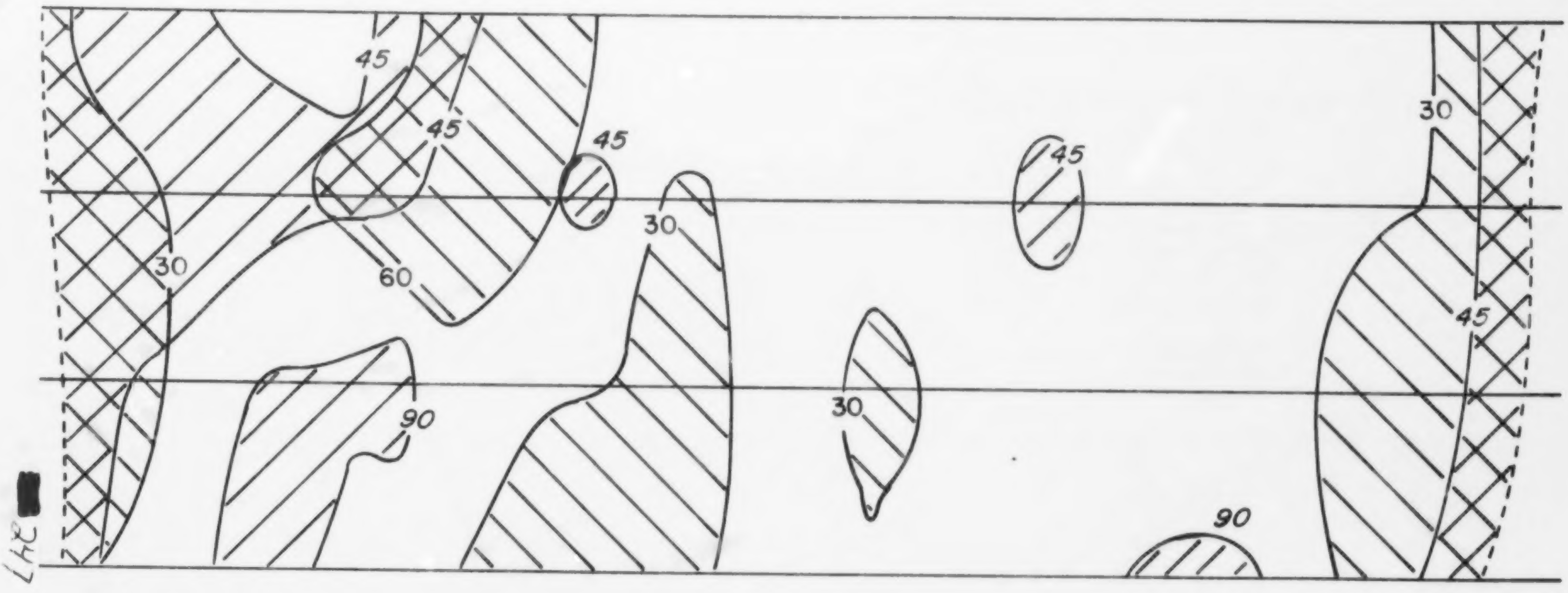
Discharge: 18.63 cms.

Area Meeting Criteria: 197 m^2

5 Meters

▧ Area not meeting depth criteria

▨ Area not meeting velocity criteria



45
45
45
30
60
30
90
45
30
90
30
45
5 Meters
▧ Area not meeting depth criteria
▨ Area not meeting velocity criteria

Figure B-9: Composite Map for the Orcutt Mapping Section, Showing Areas Meeting Flow Criteria for the Stonecat.

Discharge: 11.14 cms.

Area Meeting Criteria: 499 m^2

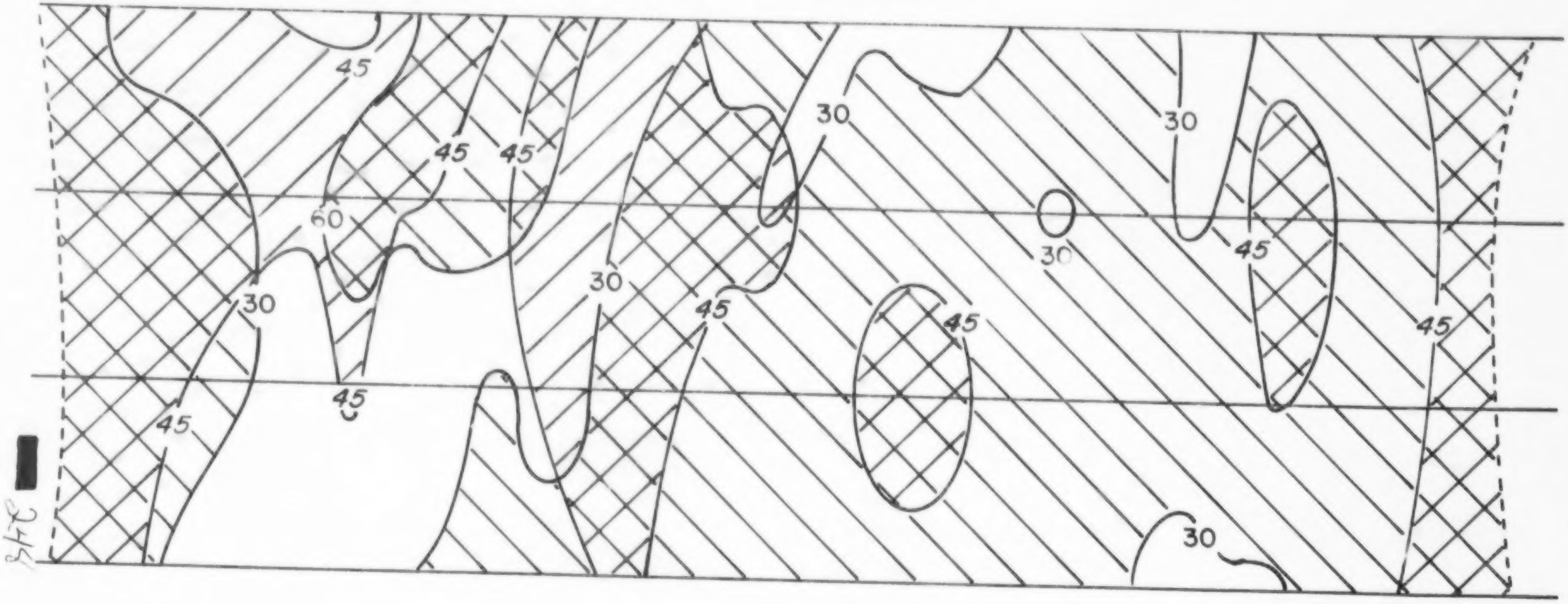

45
45
45
60
30
45
30
45
30
45
30
30
45
30
45
45
30
45
5 Meters
Area not meeting depth criteria
Area not meeting velocity criteria

Figure B-10: Composite Map for the Orcutt Mapping Section, Showing Areas Meeting Flow Criteria for the Stonecat.

Discharge: 7.58 cms.

Area Meeting Criteria: 113 m^2

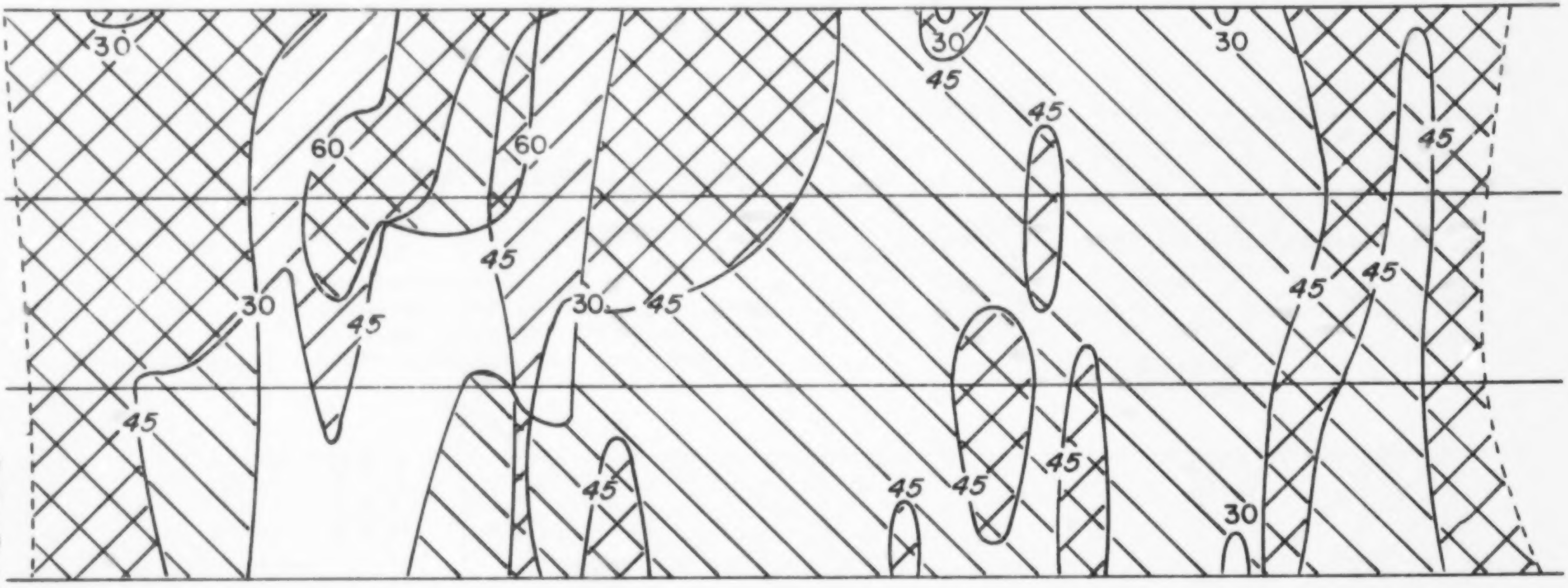


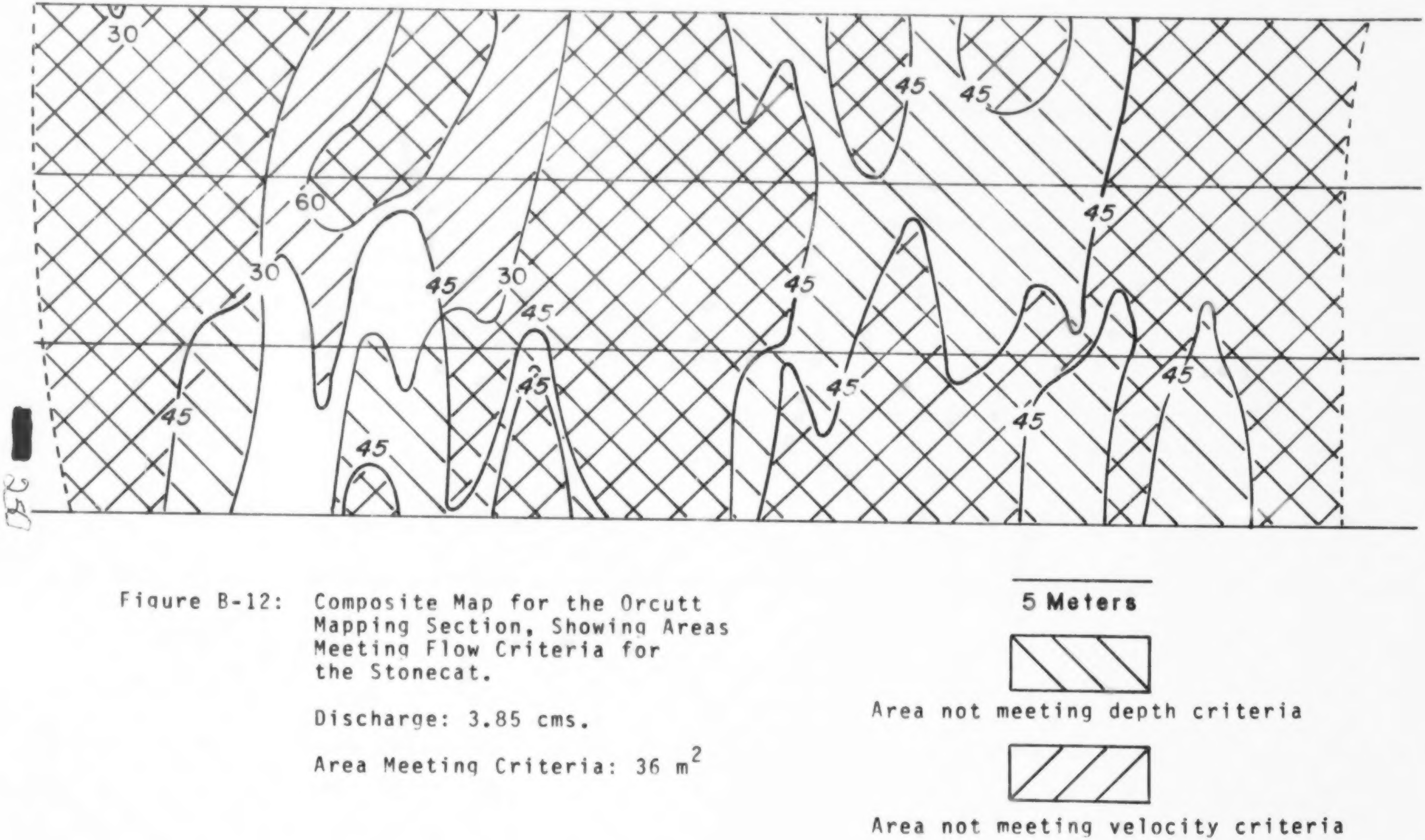
Figure B-11: Composite Map for the Orcutt Mapping Section, Showing Areas Meeting Flow Criteria for the Stonecat.

Discharge: 5.43 cms.

Area Meeting Criteria: 59 m^2

▨ Area not meeting depth criteria

▨ Area not meeting velocity criteria


30
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60
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45
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45
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45
45
45
5 Meters
Area not meeting depth criteria
Area not meeting velocity criteria

Figure B-12: Composite Map for the Orcutt Mapping Section, Showing Areas Meeting Flow Criteria for the Stonecat.

Discharge: 3.85 cms.

Area Meeting Criteria: 36 m^2

APPENDIX C

COMPOSITE MAPS

INSECT PRODUCTIVITY AREAS

1. Direction of flow is from top of page to bottom.
2. These maps indicate areas meeting preferred conditions of depth, velocity, and substrate, for optimum diversity and productivity of aquatic insects, as determined using Rhithrogena hageni as the indicator species.
3. For easier interpretation, depth contours are indicated by vertical typeface. Velocity contours are indicated by slanting typeface.
4. Cross-hatched areas on composite maps indicate areas which do not meet flow criteria for Rhithrogena hageni. Only those areas without cross-hatching meet flow criteria.
5. Dashed lines indicate water's edge, either at banks or on exposed bars.

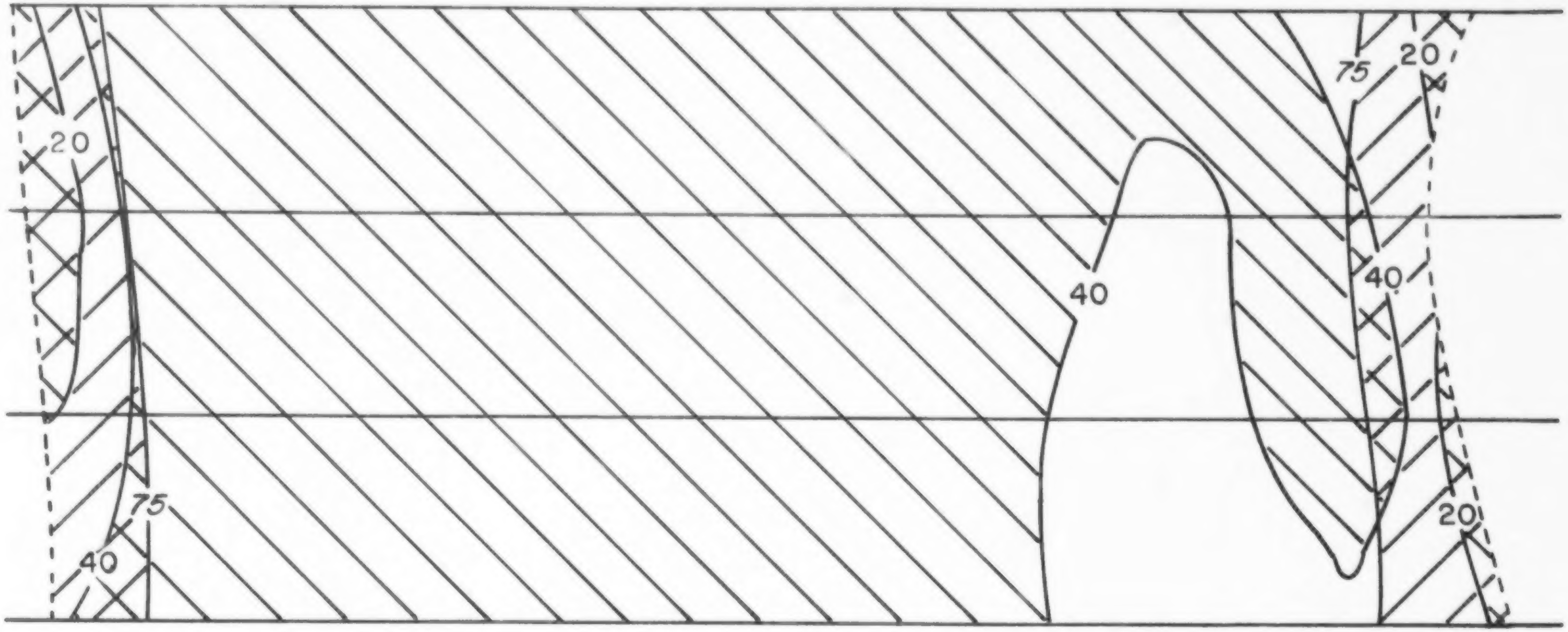


Figure C-1: Composite Map of the Viall Mapping Section Showing Areas Meeting Flow Criteria, Using Rhithrogena hageni as the Indicator Species.

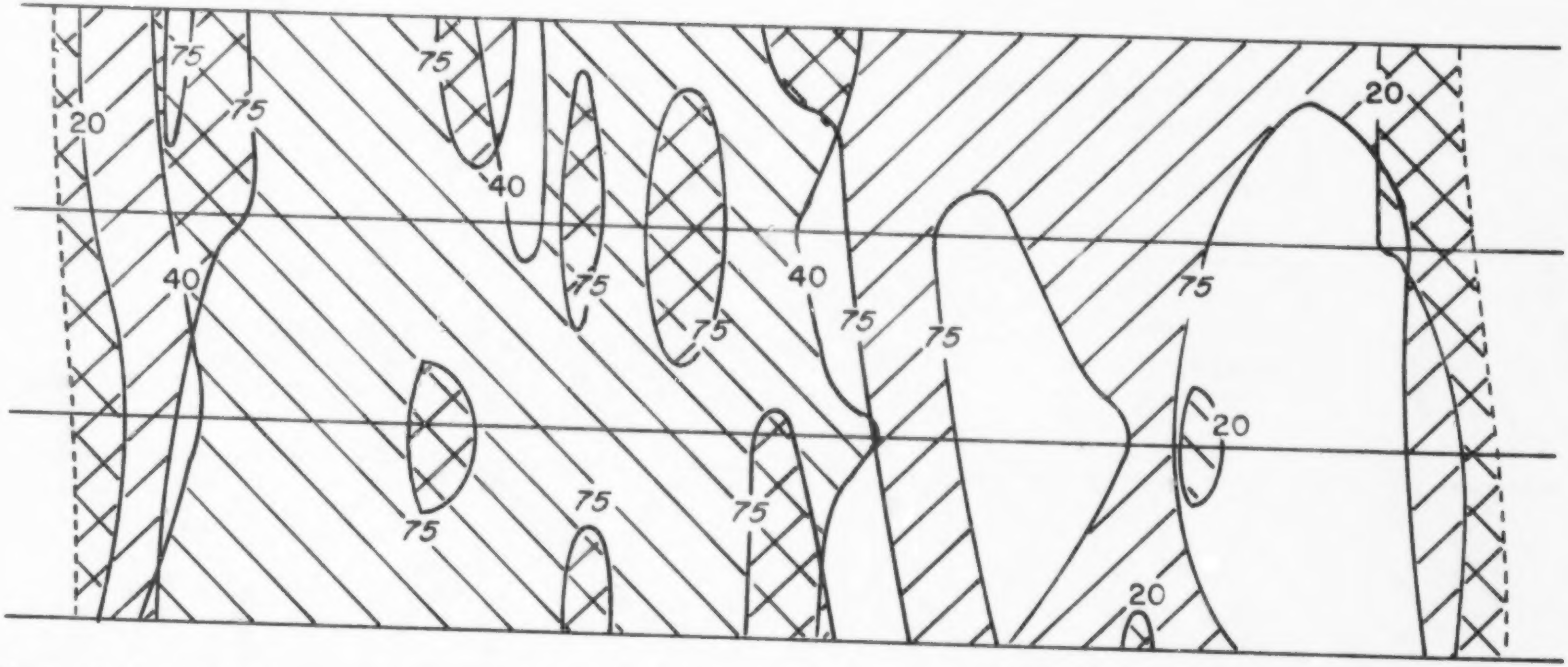
Discharge: 19.4 cms.

Area Meeting Criteria: 92 m^2

5 Meters

▧ Area not meeting depth criteria

▨ Area not meeting velocity criteria


20
75
75
40
75
40
75
75
75
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75
20
75
20
20

Figure C-2: Composite Map of the Viall Mapping Section, Showing Areas Meeting Flow Criteria, Using Rhithrogena hageni as the Indicator Species.

Discharge: 12.0 cms.

Area Meeting Criteria: 163 m^2

5 Meters
▧ Area not meeting depth criteria
▨ Area not meeting velocity criteria

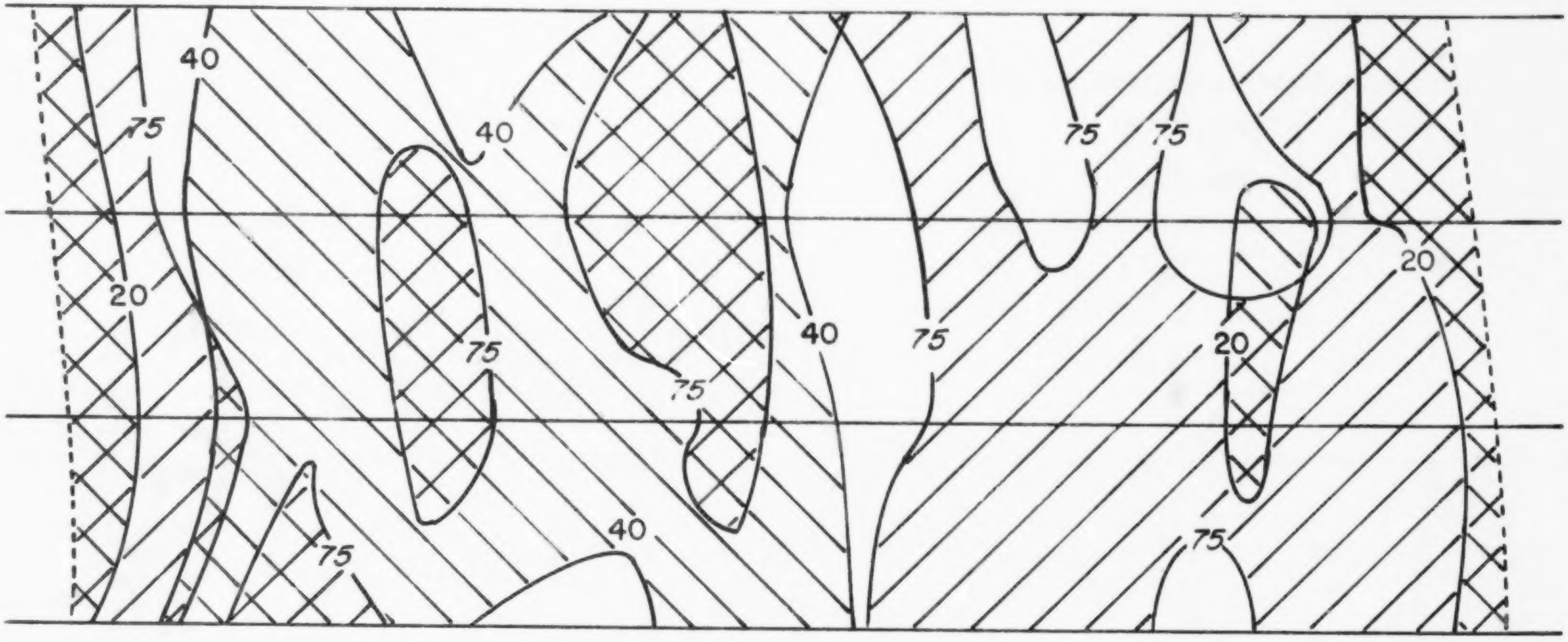


Figure C-3: Composite Map of the Viall Mapping Section, Showing Areas Meeting Flow Criteria, Using Rhitnrogena nageni as the Indicator Species.

Discharge: 10.2 cms.

Area Meeting Criteria: 73 m^2

5 Meters

▧ Area not meeting depth criteria

▨ Area not meeting velocity criteria

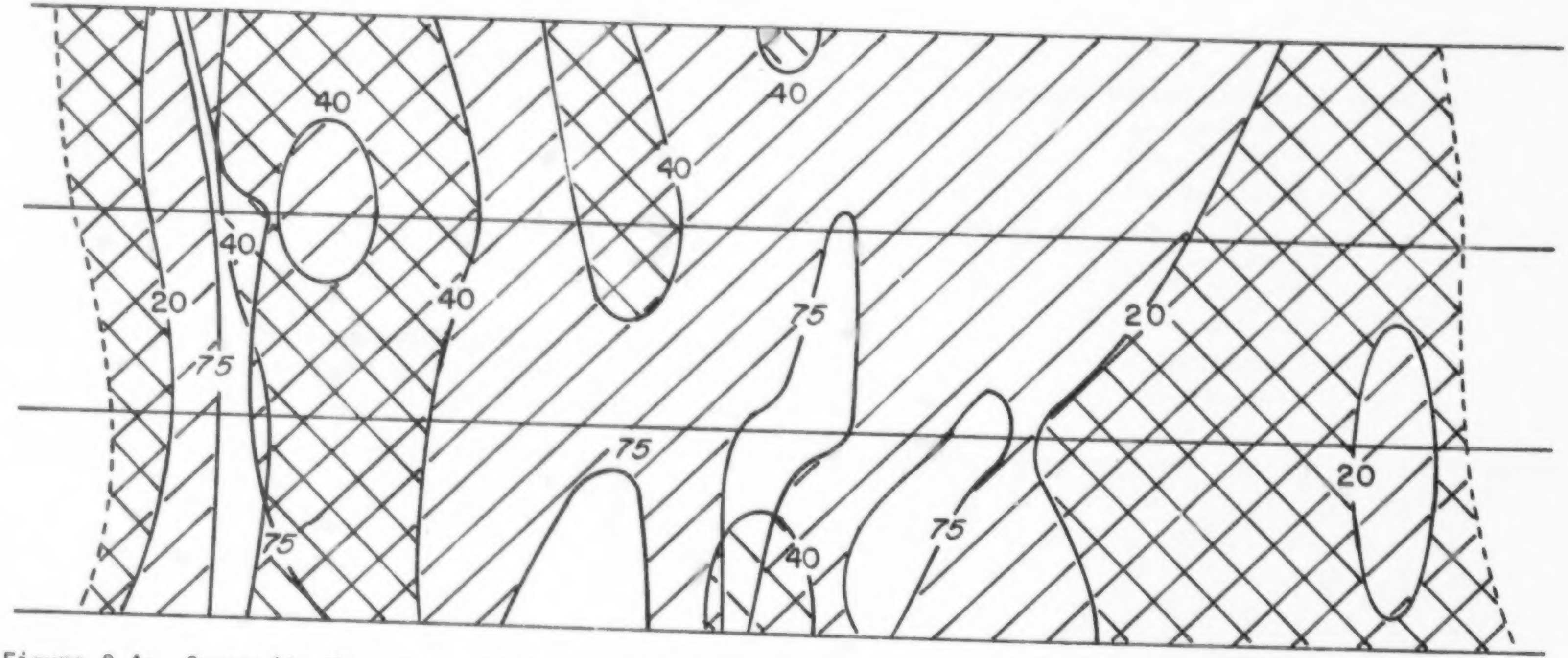

40
40
40
40
40
40
20
75
75
75
75
75
20
20
5 Meters
Area not meeting depth criteria
Area not meeting velocity criteria

Figure C-4: Composite Map of the Viall Mapping Section, Showing Areas Meeting Flow Criteria, Using Rhithrogena hageni as the Indicator Species.

Discharge: 6.3 cms.

Area Meeting Criteria: 60 m^2

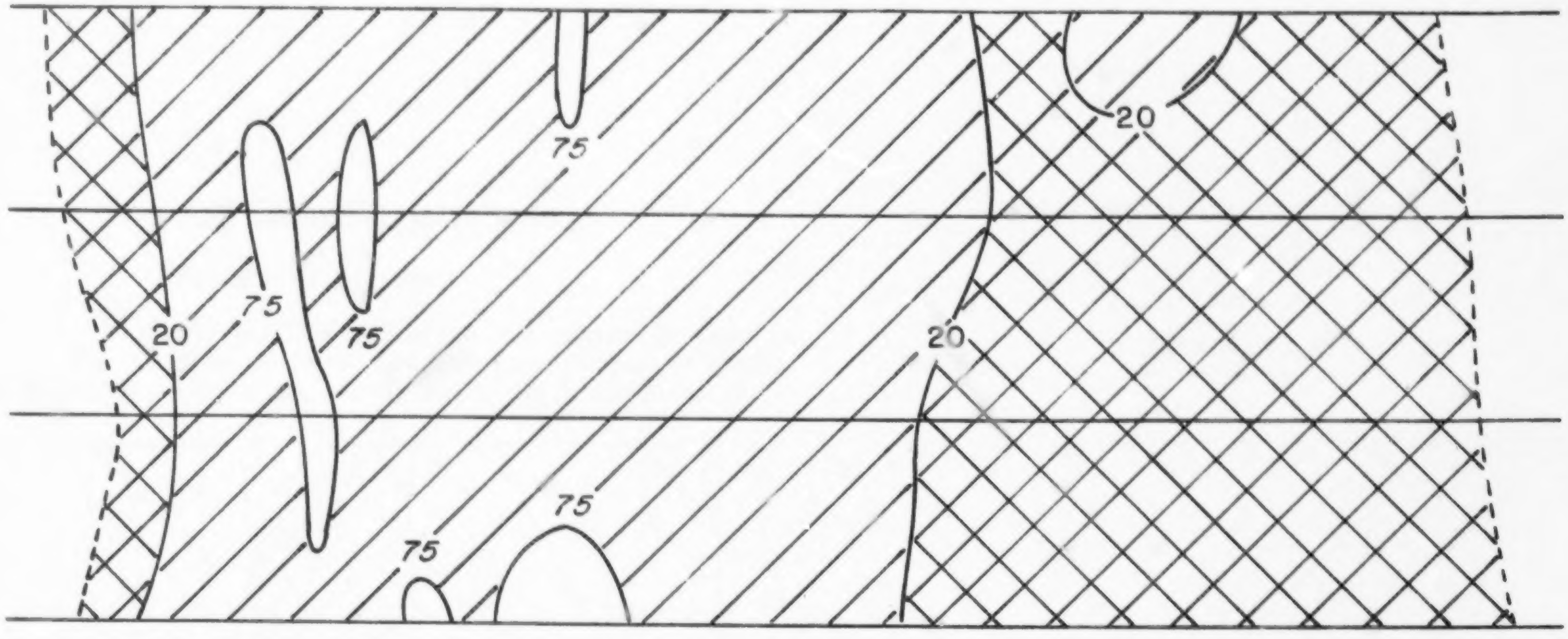


Figure C-5: Composite Map of the Viall Mapping Section, Showing Areas Meeting Flow Criteria, Using Rhithrogena hageni as the Indicator Species.

Discharge: 5.58 cms.

Area Meeting Criteria: 23 m^2

5 Meters

▧ Area not meeting depth criteria

▨ Area not meeting velocity criteria

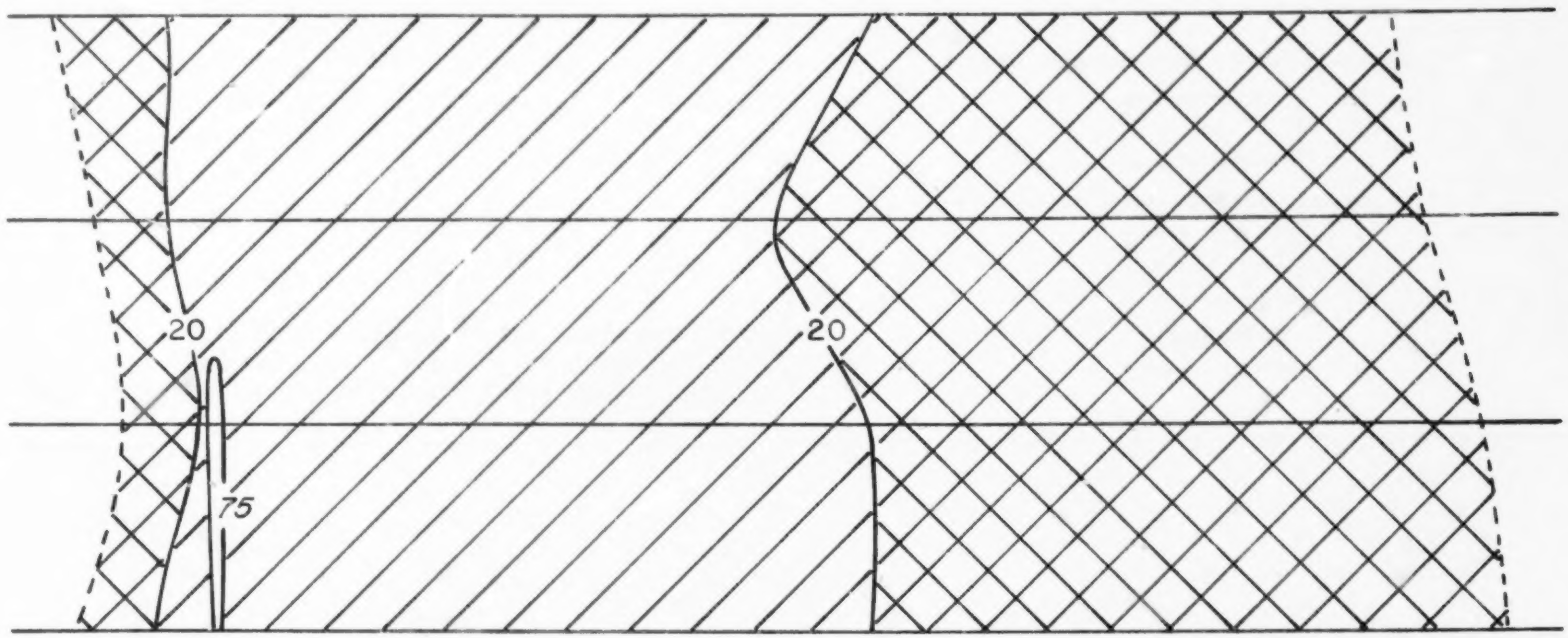


Figure C-6: Composite Map of the Viall Mapping Section, Snowing Areas Meeting Flow Criteria, Using Rhithrogena hageni as the Indicator Species.

Discharge: 4.02 cms.

Area Meeting Criteria: 3 m^2

5 Meters

▧ Area not meeting depth criteria

▨ Area not meeting velocity criteria

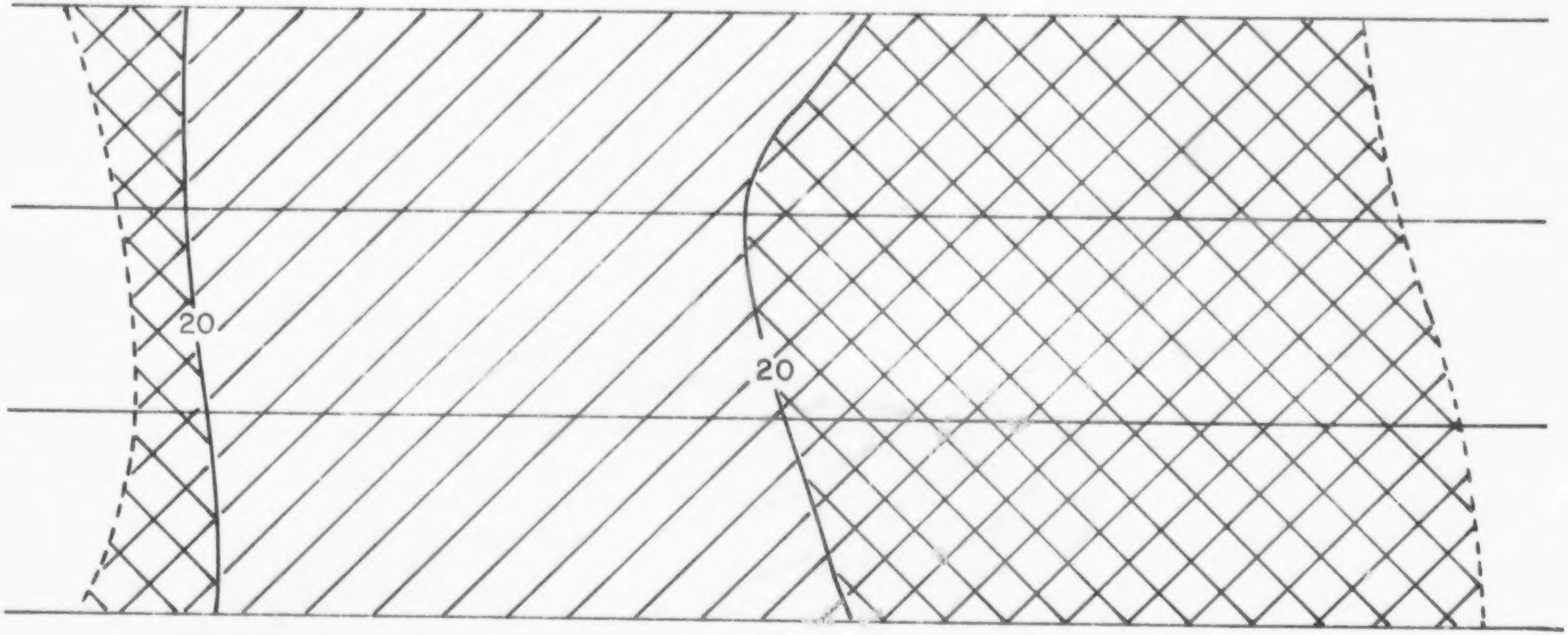


Figure C-7: Composite Map of the Viall Mapping Section, Showing Areas Meeting Flow Criteria, Using Rhitnrogena hageni as tne Indicator Species.

Discharge: 2.83 cms.

Area Meeting Criteria: 0 m^2

5 Meters

▧ Area not meeting depth criteria

▨ Area not meeting velocity criteria

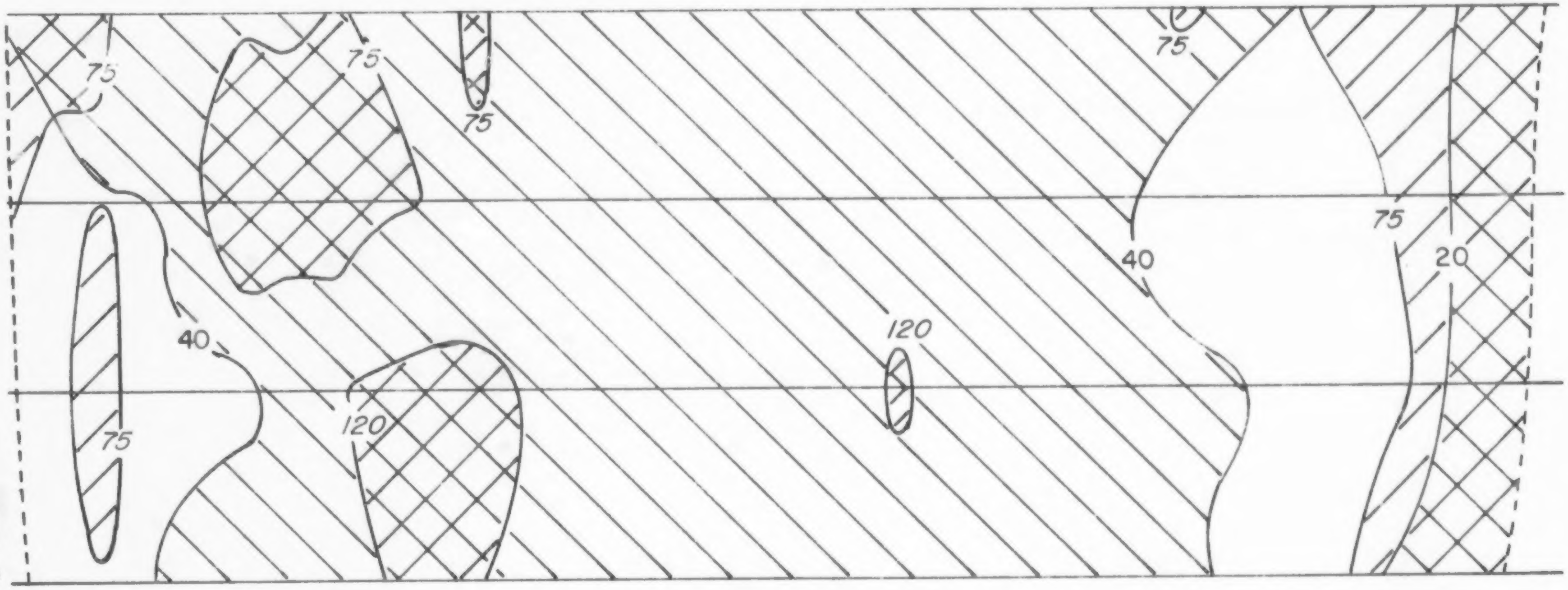


Figure C-8: Composite Map of the Orcutt Mapping Section, Showing Areas Meeting Flow Criteria, Using Rhithrogena nageni as the Indicator Species.

Discharge: 18.63 cms.

Area Meeting Criteria: 147 m^2

5 Meters

▧ Area not meeting depth criteria

▨ Area not meeting velocity criteria

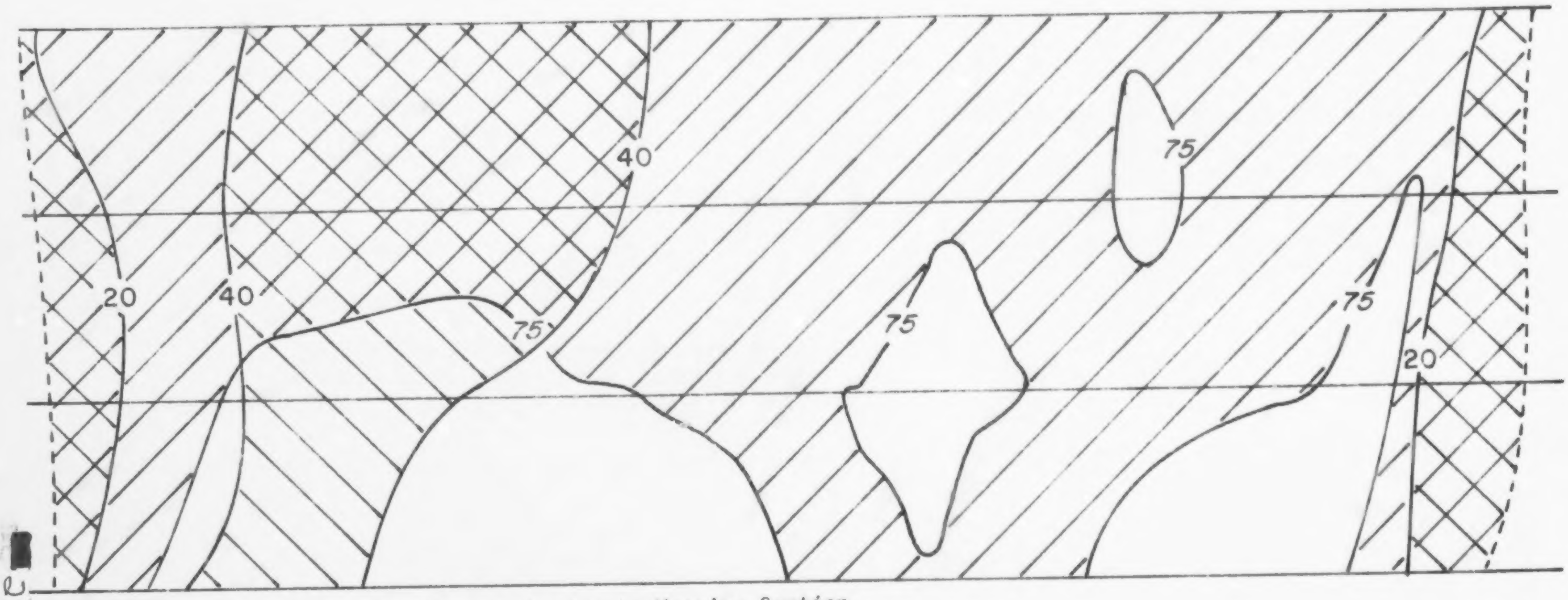


Figure C-9: Composite Map of the Orcutt Mapping Section Showing Areas Meeting Flow Criteria, Using Rhithrogena hageni as the Indicator Species.

Discharge: 11.14 cms.

Area Meeting Criteria: 177 m^2

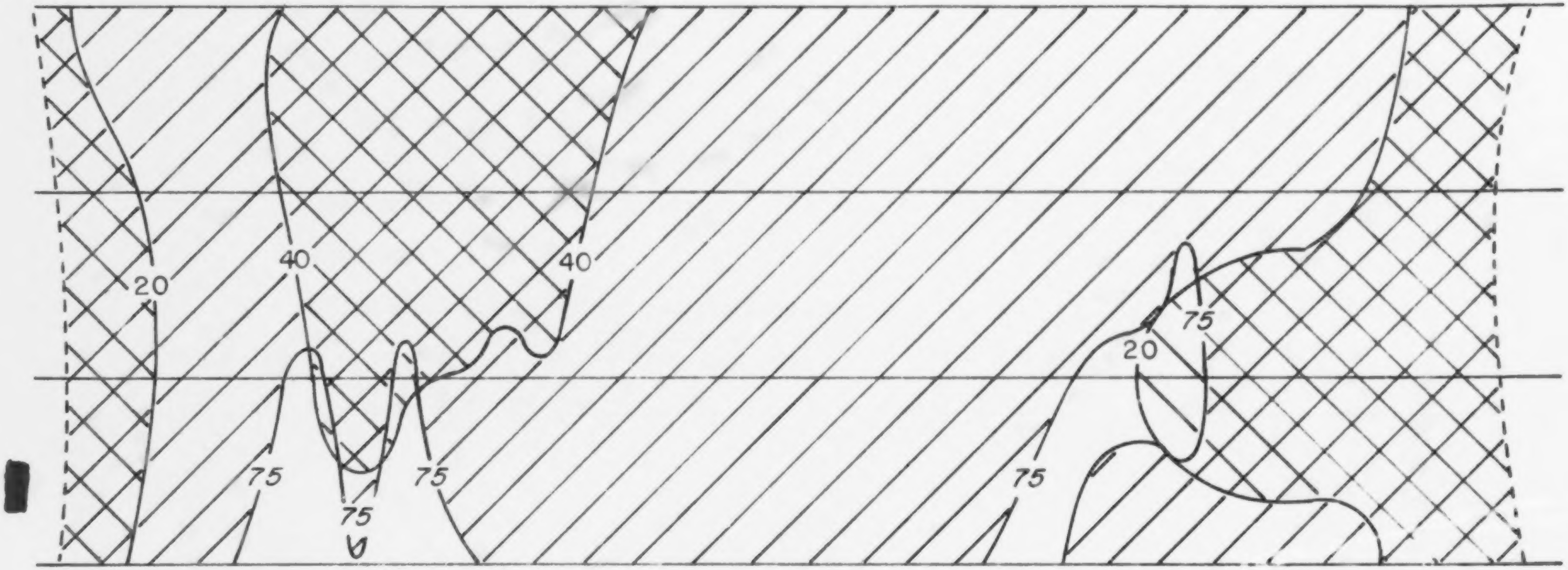
5 Meters

▧

Area not meeting depth criteria

▨

Area not meeting velocity criteria


20
40
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20
75

Figure C-10: Composite Map of the Urcutt Mapping Section, Showing Areas Meeting Flow Criteria, Using Rhithrogena hageni as tne Indicator Species.

Discharge: 7.58 cms.

Area Meeting Criteria: 72 m^2

5 Meters
▧ Area nct meeting depth criteria
▨ Area not meeting velocity criteria

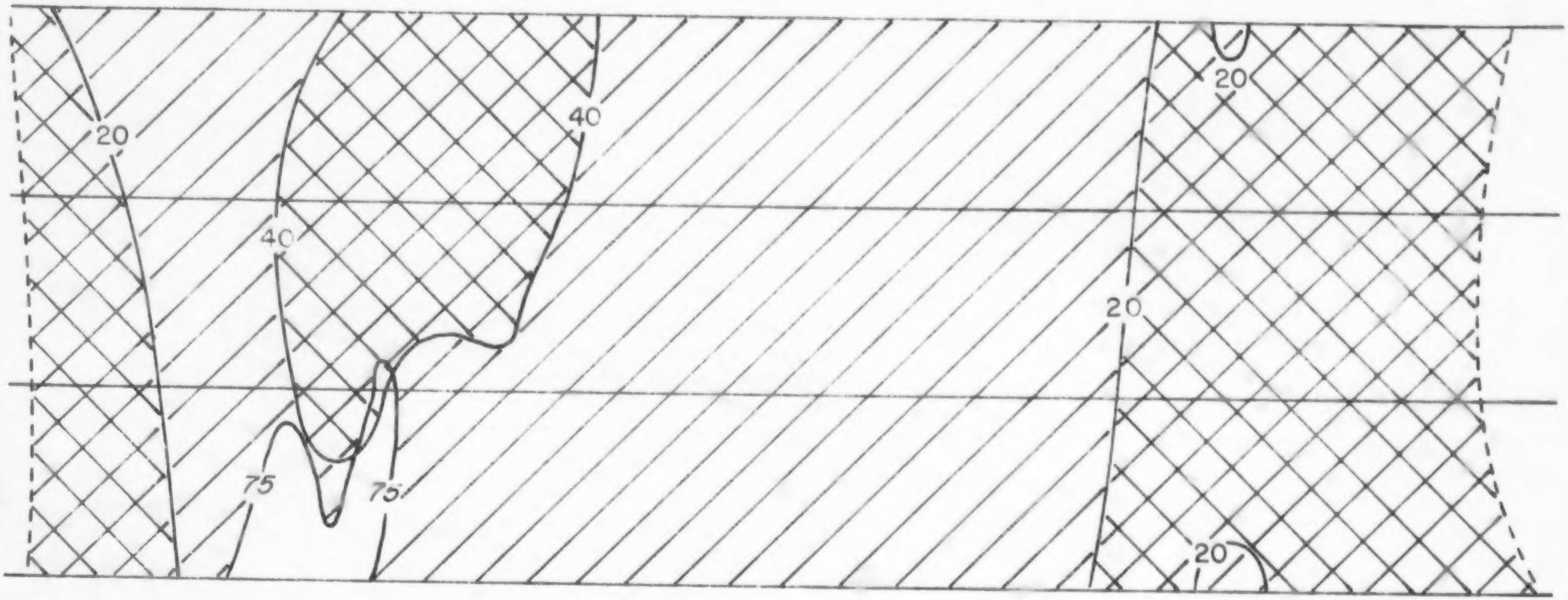

Figure C-11: Composite Map of the Orcutt Mapping Section, Showing Areas Meeting Flow Criteria, Using Rhitnrogena hageni as the Indicator Species.

Discharge: 5.43 cms.

Area Meeting Criteria: 20 cms.

5 Meters

▧ Area not meeting depth criteria

▨ Area not meeting velocity criteria

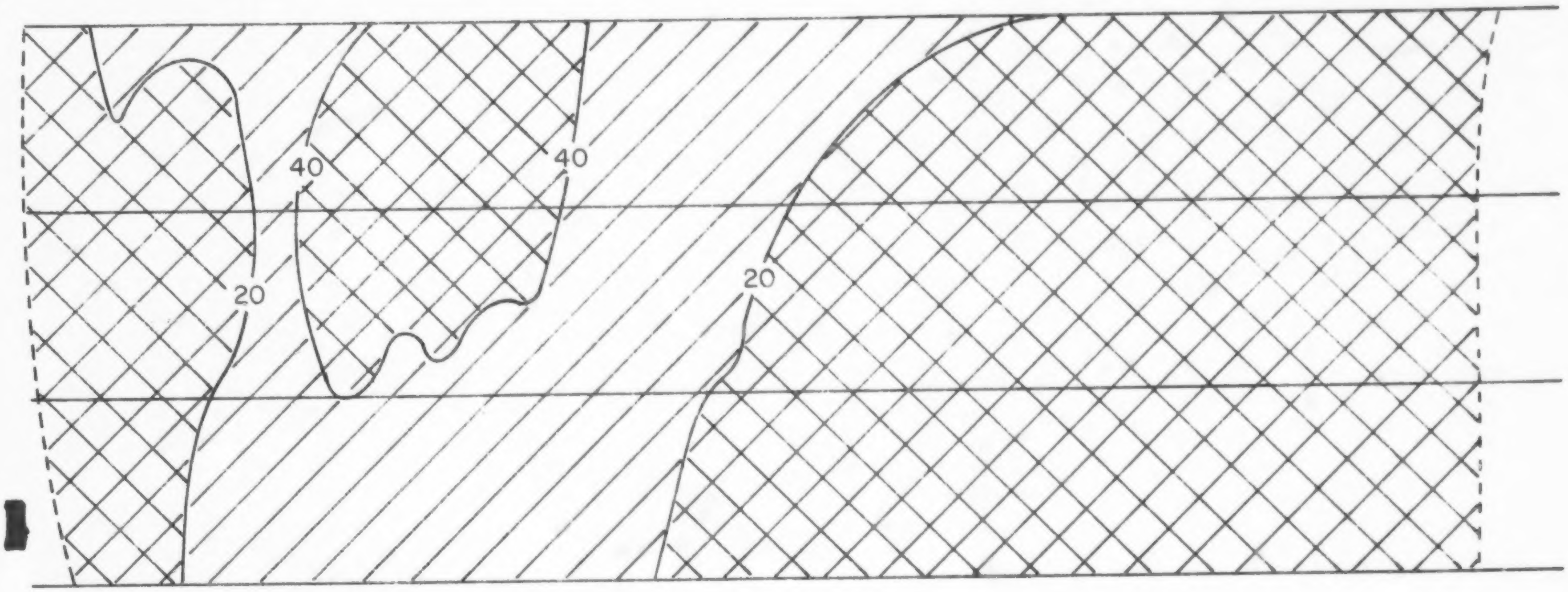

Figure C-12: Composite Map of the Orcutt Mapping Section, Showing Areas Meeting Flow Criteria, Using *Rhithrogena hageni* as the Indicator Species.

Discharge: 3.85 cms.

Area Meeting Criteria: 0 m^2

5 Meters

▧ Area not meeting depth criteria

▨ Area not meeting velocity criteria

APPENDIX D

MACROINVERTEBRATE ECOLOGY

APPENDIX D: MACROINVERTEBRATE ECOLOGY

Microprofile Measuring Device

Measurement of the exact composition of the substrate would be an extremely long and time consuming process for each of 175 samples collected in this study. However, the nature of the substrate material determines the profile of the substrate, and it is this profile to which the invertebrates must adapt in order to obtain habitable conditions of current velocity. The index of the profile can provide, with proper interpretation, information on the roughness of the substrate and surface area availability. The method used allows the investigator to measure the substrate profile, before sampling benthic organisms, without having to map the position of the substrate particles or physically remove portions of the substrate for measurement. In this manner, a given piece of substrate can be rapidly recolonized so that samples on the same substrate can be taken again, if necessary.

The prototypic device is designed to fit within a Hess Bottom sampler. The micro-profile sampler is constructed using a circular sheet of plexiglass (about 1 cm. thick) with a diameter of 35.68 cm., to give a tenth-square-meter surface area (see Figure D1). The sheet is prepared by drilling holes in a grid pattern such that 21 holes are placed at 5 cm. intervals in the grid pattern. The holes are drilled large enough to accept 21 threaded steel rods of about 8 mm. diameter (rods of smaller diameter cause too much free play on the plexiglass sheet to be effective). Three of the steel rods are fixed to the sheet at a standard distance of 17.5 cm. from the bottom surface of the sheet with a system of washers, lock washer, and nuts to fit the threaded rods. These three supportive legs are placed to form a uniform triangle in three outer grid holes.

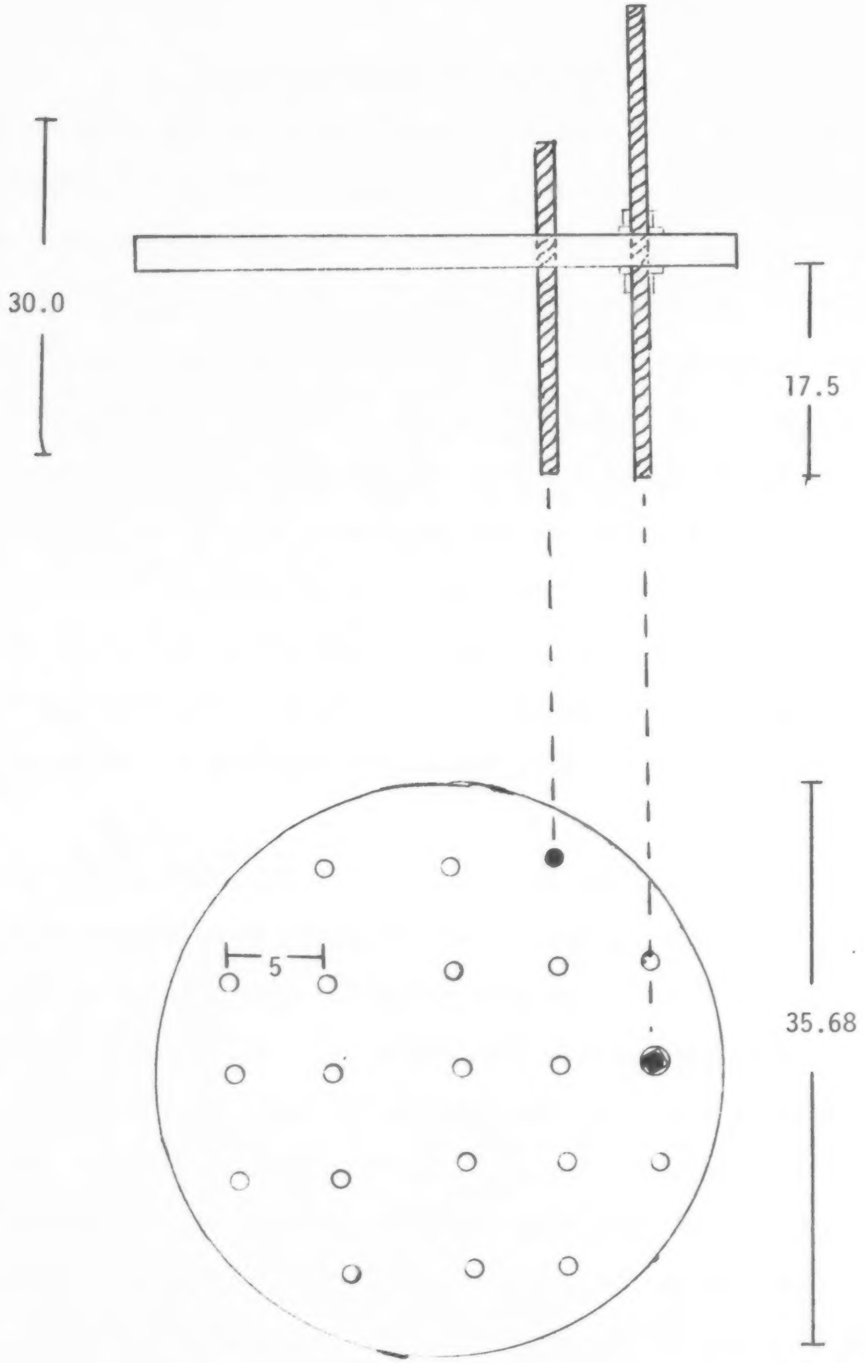

Figure D1. Schematic of Microprofile Measuring Device.
All measurements are in cm.

This device is then placed within the Hess sampler, which has been previously placed in the water upon the substrate area to be sampled. The fixed legs, which provide a "zero" reference point, should be maneuvered to be as close to the base substrate as possible; that is, not upon any large objects protruding from the substrate surface. The remaining 18 rods, each 30 cm. long, are allowed to fall vertically within their respective grid holes. As the rods make contact with various objects on the substrate the rods are clamped (a standard barrel-type pinch clamp is suitable) at the upper surfaces of the plexigless sheet to prevent further movement.

When all rods have been placed, the device can be removed from the Hess sampler (using the fixed legs as handles) and invertebrate sampling can continue by normal procedure. Once the device is removed, the length of the 18 "free" rods are measured from the plexiglass surface to the tip of the rod. If the grid is numbered and the rods are measured and recorded, a three-dimensional schematic drawing of the substrate can be made. The distances to be schematically represented are the lengths of the 18 "free" rods minus the length of a "standard" rod which has been allowed to fall to a flat surface upon which the device is also sitting. The standard deviation of the mean length of the 21 rods (where the three fixed rods are "standard" length) provides a single descriptive index (I) which is useful in habitat description. The index numbers are defined below:

I	PROFILE TYPE
0 - 0.5	Smooth
0.5 - 1.0	Moderately smooth (gravel)
1.0 - 1.5	Small cobbled
1.5 - 2.0	Smooth, medium cobbled
2.0 - 2.5	Rough, medium cobbled
2.5 - 3.0	Large cobbled
3.0 - 4.0	Bouldered
4.0	Critical (angular boulders)

Velocity, depth, micro-profile, and turbulence (by Froude number, F), where:

$$F = \frac{V}{\sqrt{g\ D}} \qquad \text{(Eq. D-1)}$$

and; V = current velocity in cm./sec.

D = depth in centimeters

g = acceleration due to gravity (980 cm./sec^2.)

were compared with diversity of insects in the sample and number of individuals of a given species per sample, in order to determine optimum flow related conditions.

Flow Related Requirements For Macroinvertebrates

The following figures and tables illustrate the optimum conditions of depth, velocity, turbulence, and microprofile for the invertebrates examined. The large square on the velocity and depth Figures (D1 - D31) is the area representing conditions of maximum diversity (also Table D-1). The calculations for this area, the COCD, and the optimum centroids for the individual macroinvertebrates, are described in Chapter 5 of the report. In addition, the area where at least 80% of the macroinvertebrates occurred is also shown on each of the figures (D2 - D31). The centroids, like the COCD, describe the optimum point on the surface for either velocity, depth, and number of individuals, or turbulence, microprofile, and number of individuals. A definite area of maximum diversity was not defined in the relation between microprofile and turbulence (Table D-2). It can be assumed that the maximum diversity area will be generally located in close proximity to the COCD for microprofile and turbulence.

D V	0 - 10	10 - 20	20 - 30	30 - 40	40 - 50
0 - 15	.667	1.112	1.405	1.530	1.371
16 - 30	1.348	1.218	1.957	1.054	1.505
31 - 45	1.628	1.893	1.977	1.933	1.845
46 - 60	1.440	1.721	1.605	1.958	1.812
61 - 75	1.523	1.703	1.728	2.034	1.612
76 - 90	1.652	1.809	2.319	2.190	2.156
91 - 105	1.203	1.983	2.211	1.844	2.072
105-120	1.386	1.661	2.612	2.027	1.724
>120	.541	1.802	2.131	2.301	1.817

Table D1. Average Diversities for Depth and Velocity. Average diversity for all samples that occured within the block represented by the increments of depth and current velocity. Current velocity in cm./sec. Depth in cm.

F \ I	.5 - 1.0	1 - 1.5	1.5 - 2.0	2 - 2.5	2.5 - 3	3 - 4
0 - .1		1.399	1.327	1.744		
.1 - .2	1.609		1.356	1.400	1.995	
.2 - .3		2.119	2.099	2.000	1.657	
.3 - .4	1.310	1.871	1.589	1.978	2.064	
.4 - .5	1.946	2.080	1.745	2.017	1.959	2.366
.5 - .6		2.763	2.040	1.560	1.072	
.6 - .7			2.111	1.875		2.6000
>.7	1.476			2.025	1.750	

Table D2. Average Diversities for Microprofile and Turbulence. Average diversity for all samples that occured within the blocks represented by the increments of microprofile and turbulence.

Table D-3: Centroids of optimum velocity (C_v), depth (C_d), microprofile index (C_i), and Froude Number (C_f) for 38 species of macroinvertebrates in the Tongue River. Depths and velocities have been rounded to the nearest cm. and cm./sec., respectively.

Species	C_v	C_d	C_i	C_f
DIVERSITY	76.	28.	2.01	.401
Ephoron album	97.	30.	2.03	.557
Baitis tricaudatus	74.	28.	2.01	.411
Baetis alexanderi	55.	23.	1.80	.392
Ephemerella margarita	84.	25.	1.99	.502
Ephemerella hystrix	82.	29.	2.05	.526
Tricorythodes minutus	68.	33.	2.00	.356
Choroterpes albiannulata	62.	27.	2.07	.425
Traverella albertana	80.	32.	2.14	.499
Stenonema reesi	60.	27.	1.73	.336
Rhithrogena hageni	82.	32.	2.07	.454
Strophopteryx fasciata	73.	19.	1.97	.478
Paraleuctra sara	74.	15.	2.10	.500
Capnia limata	56.	23.	2.19	.348
Isogenoides frontalis	71.	36.	2.24	.402
Acroneuria abnormis	81.	27.	1.99	.505
Ophiogomphus morrisoni	73.	28.	2.24	.376
Hydroptila sp.	63.	30.	2.09	.343
Cheumatopsyche sp.	74.	33.	2.16	.396
Hydropsyche bifida	76.	33.	2.10	.450
Hydropsyche occidentalis	66.	26.	1.95	.417

Table D-3 (Con't)

Species	C_v	C_d	C_i	C_f
Hydropsyche sp. a	83.	34.	2.07	.462
Hydropsyche sp. b	83.	35.	1.87	.390
Hydropsyche sp. c	61.	31.	2.03	.321
Brachycentrus americanus	68.	28.	1.94	.357
Leptocella sp.	52.	29.	1.74	.274
Athripsodes sp.	79.	27.	1.97	.404
Rhagovelia sp.	22.	31.	2.21	.155
Stenelmis sp. a (1)	72.	30.	2.05	.405
Stenelmis sp. a (a)	73.	29.	2.26	.403
Stenelmis sp. b (1)	62.	25.	1.89	.385
Stenelmis sp. b (a)	70.	33.	1.96	.358
Dubiraphia sp.	57.	28.	1.55	.347
Simulium sp.	78.	27.	2.23	.495
Metriocnemus sp.	78.	31.	1.83	.443
Sphaerium simile	92.	34.	2.00	.500
Physa gyrina	93.	39.	1.82	.421
Dugesia tigrina	48.	23.	1.80	.309

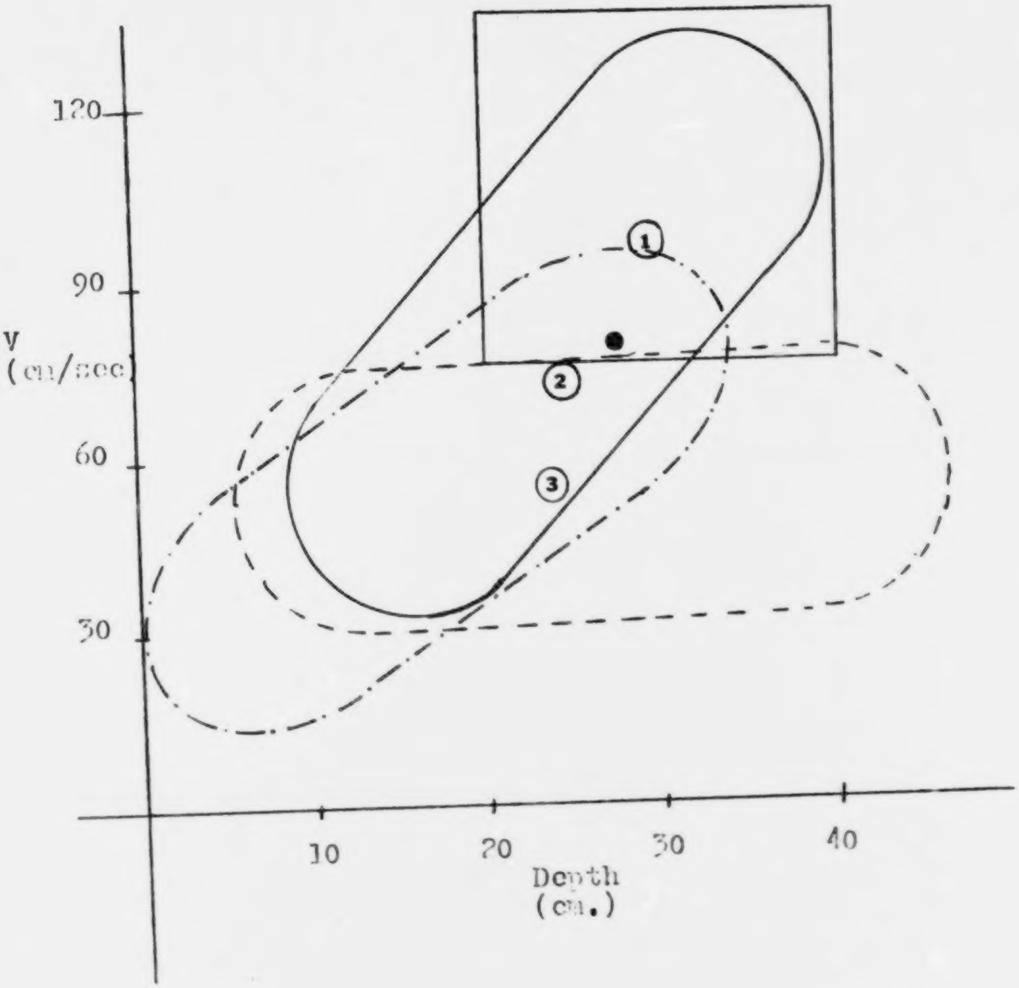

Figure D2. Optimum Depth and Current Velocities. Ephemeroptera. Ephoron album (1 and solid line), Baetis tricaudatus (2 and dashed line), and Baetis alexanderi (3 and alternating dashed and dotted line).

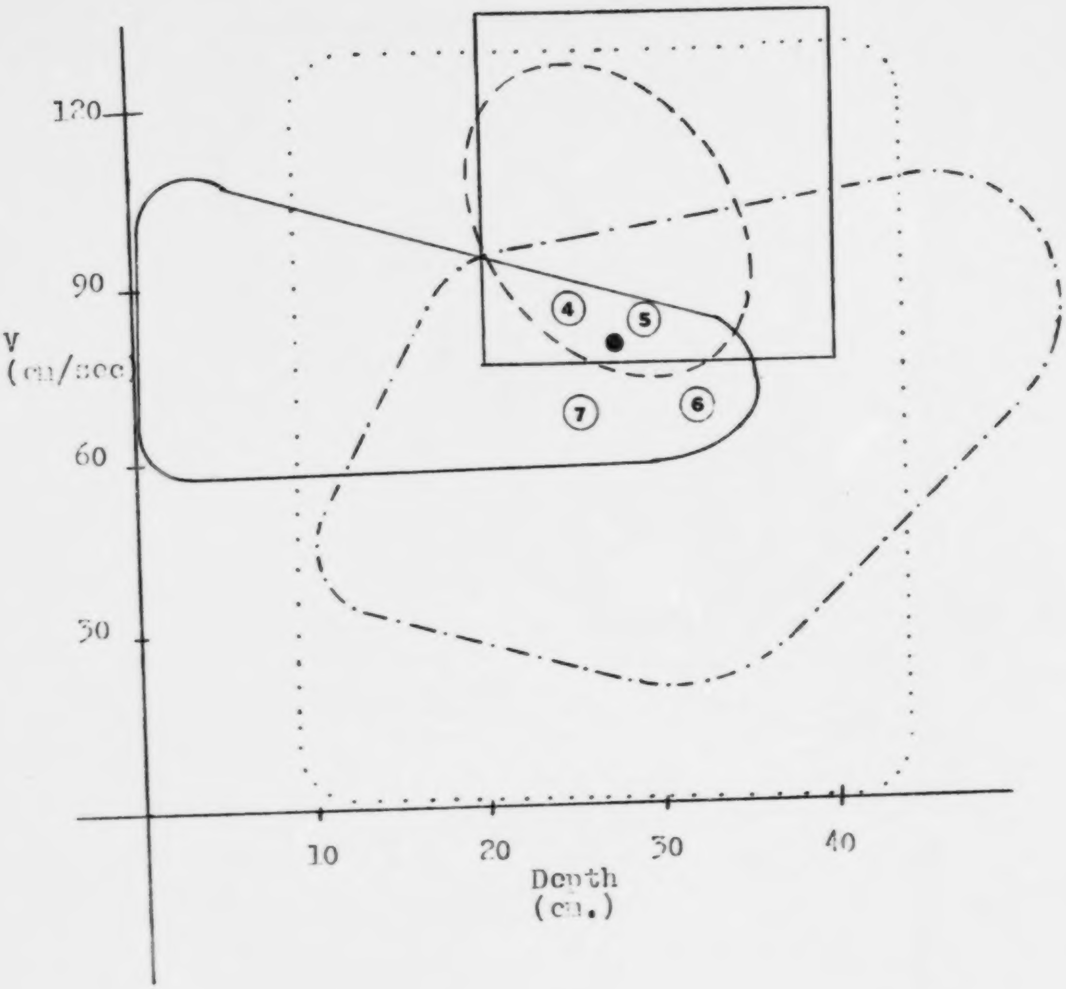

Figure D3. Optimum Depth and Current Velocities. Ephemeroptera. Ephemerella margarita (4 and solid line), Ephemerella hystrix (5 and dashed line), Tricorythodes minutus (6 and alternating dashed and dotted line), and Choroterpes albiannulata (7 and dotted line).

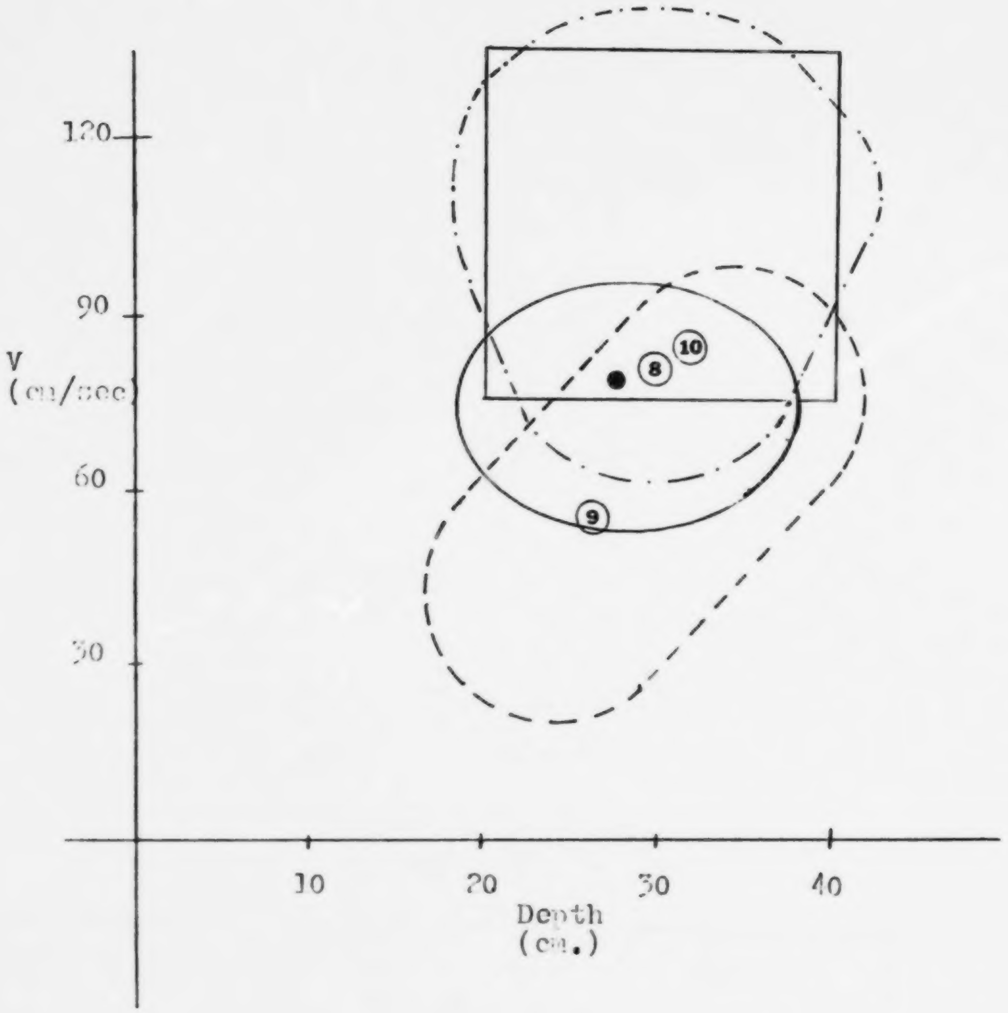

Figure D4. Optimum Depth and Current Velocities. Ephemeroptera. Traverella albertana (8 and solid line), Stenonema reesi (9 and dashed line), and Rhithrogena hageni (10 and alternating dashed and dotted line).

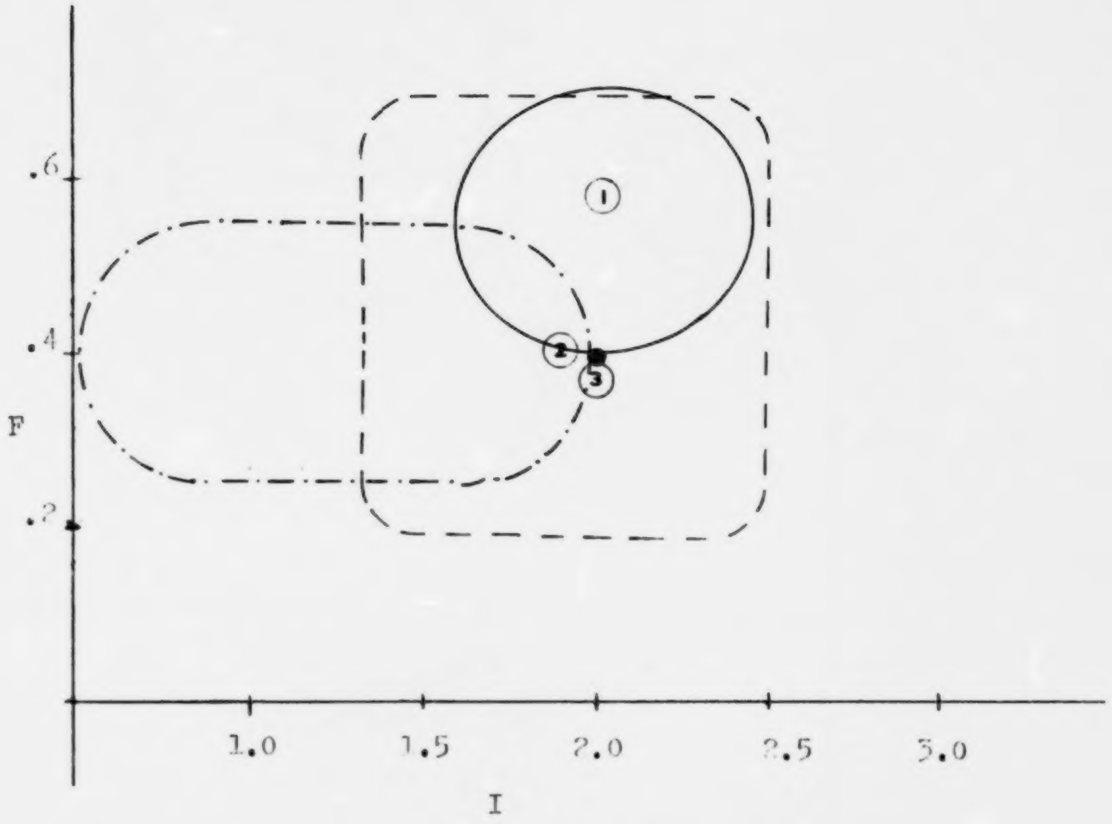

Figure D5. Optimum Turbulence and Microprofile. Ephemeroptera. Ephoron album (1 and solid line), Baetis tricaudatus (2 and dashed line), and Baetis alexanderi (3 and alternating dashed and dotted line).

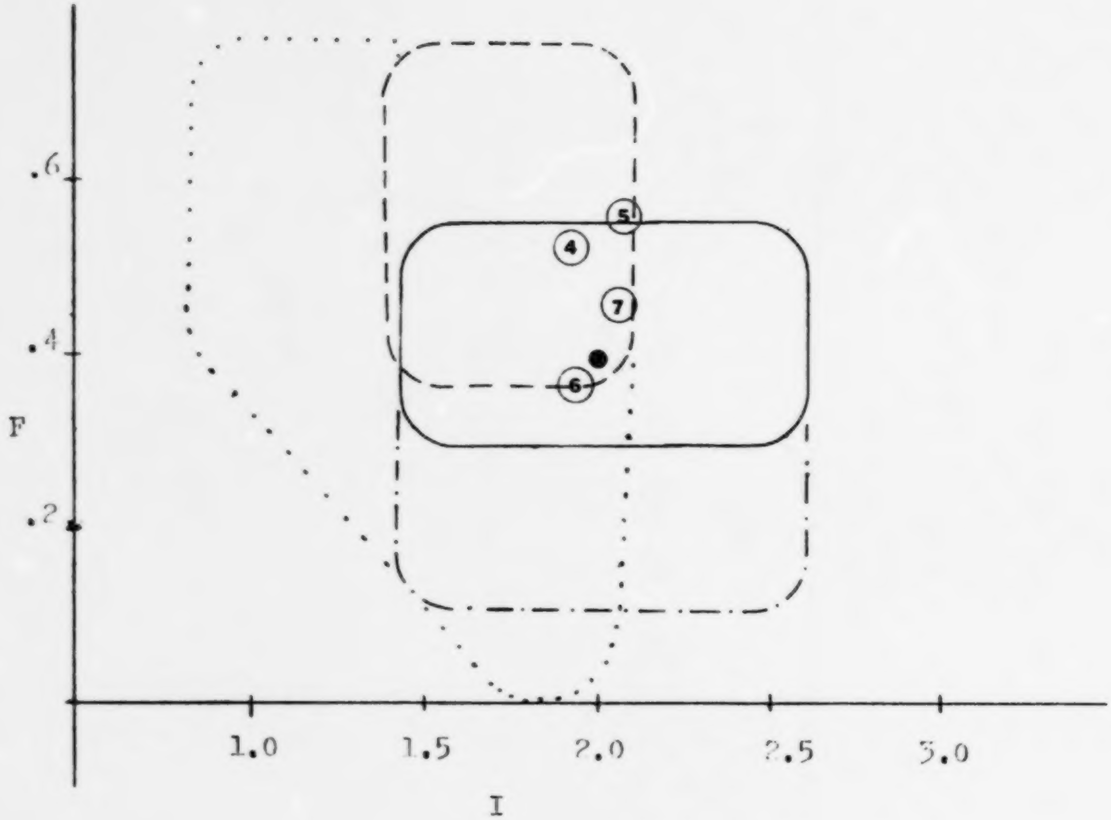

Figure D6. Optimum Turbulence and Microprofile. Ephemeroptera. Ephemerella margarita (4 and solid line), Ephemerella hystrix (5 and dashed line), Tricorythodes minutus (6 and alternating dashed and dotted line), and Choroterpes albiannulata (7 and dotted line).

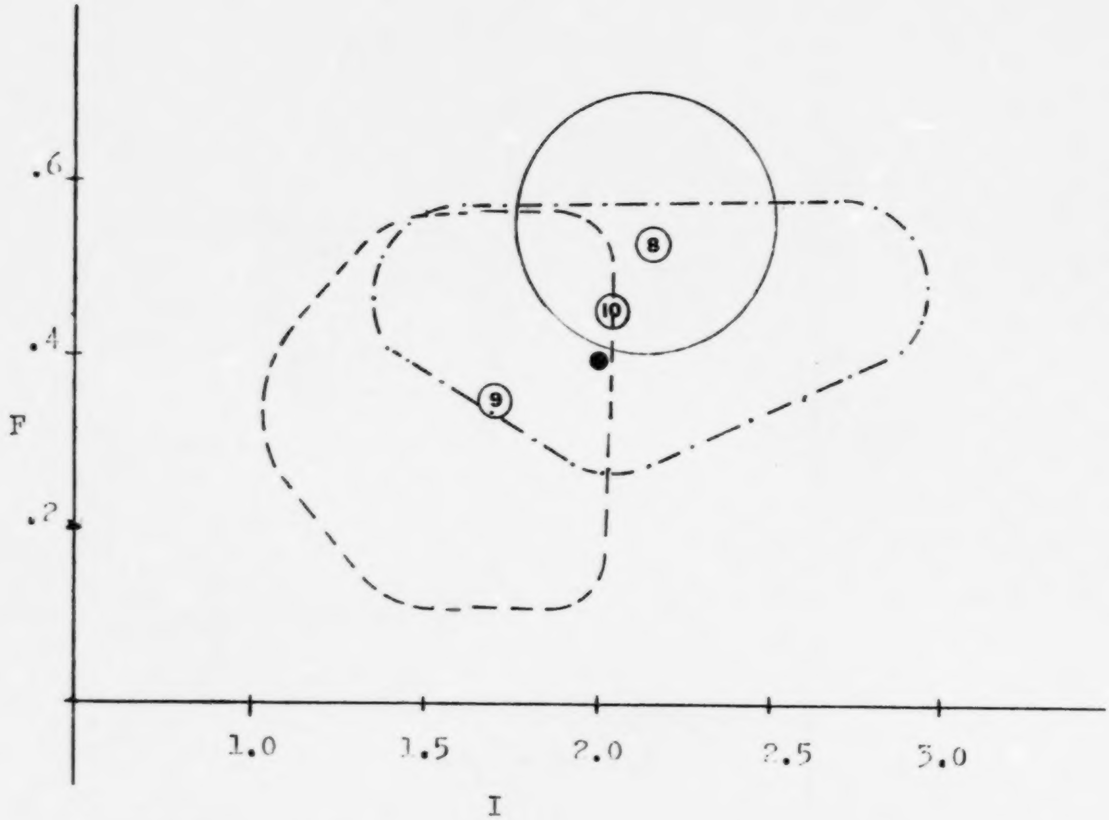

Figure D7. Optimum Turbulence and Microprofile. Ephemeroptera. Traverella albertana (8 and solid line), Stenonema reesi (9 and dashed line), and Rhithrogena hageni (10 and alternating dashed and dotted line).

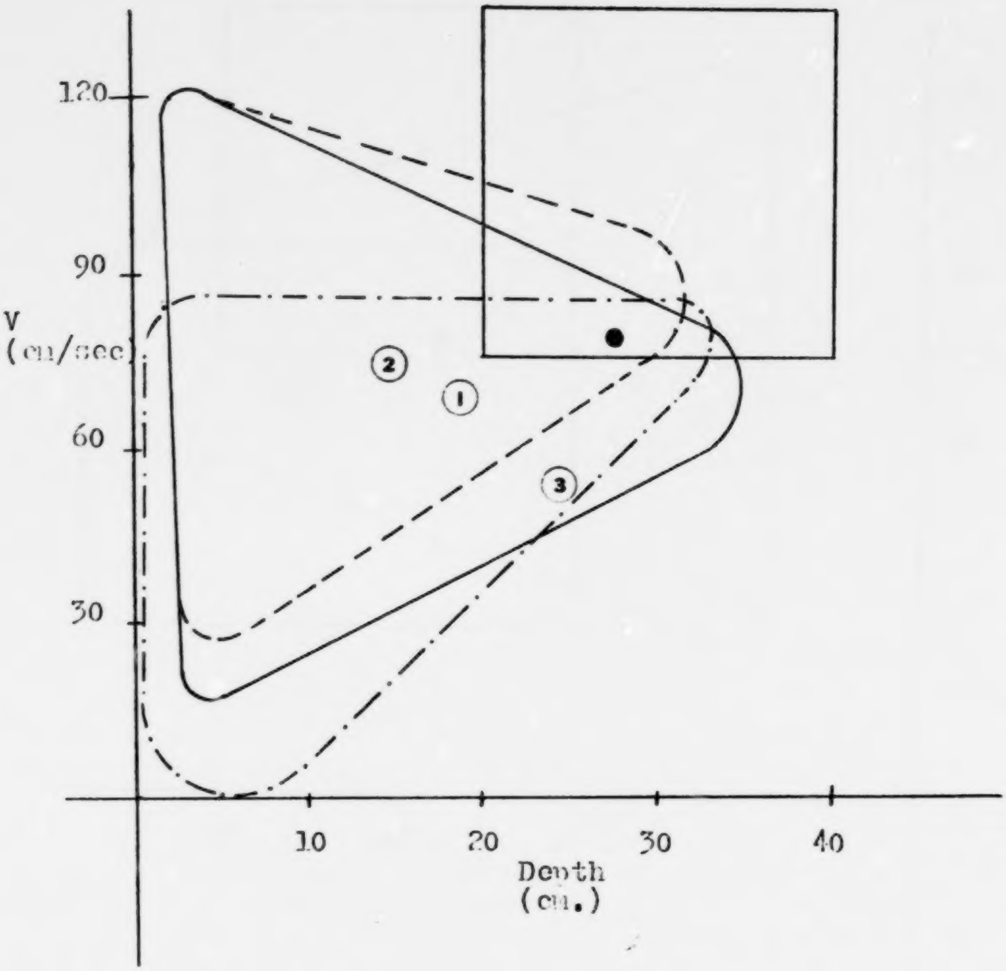

Figure D8. Optimum Depths and Current Velocities. Plecoptera. Strophopteryx fasciata (1 and solid line), Paraleuctra sara (2 and dashed line), and Capnia limata (3 and alternating dashed and dotted line).

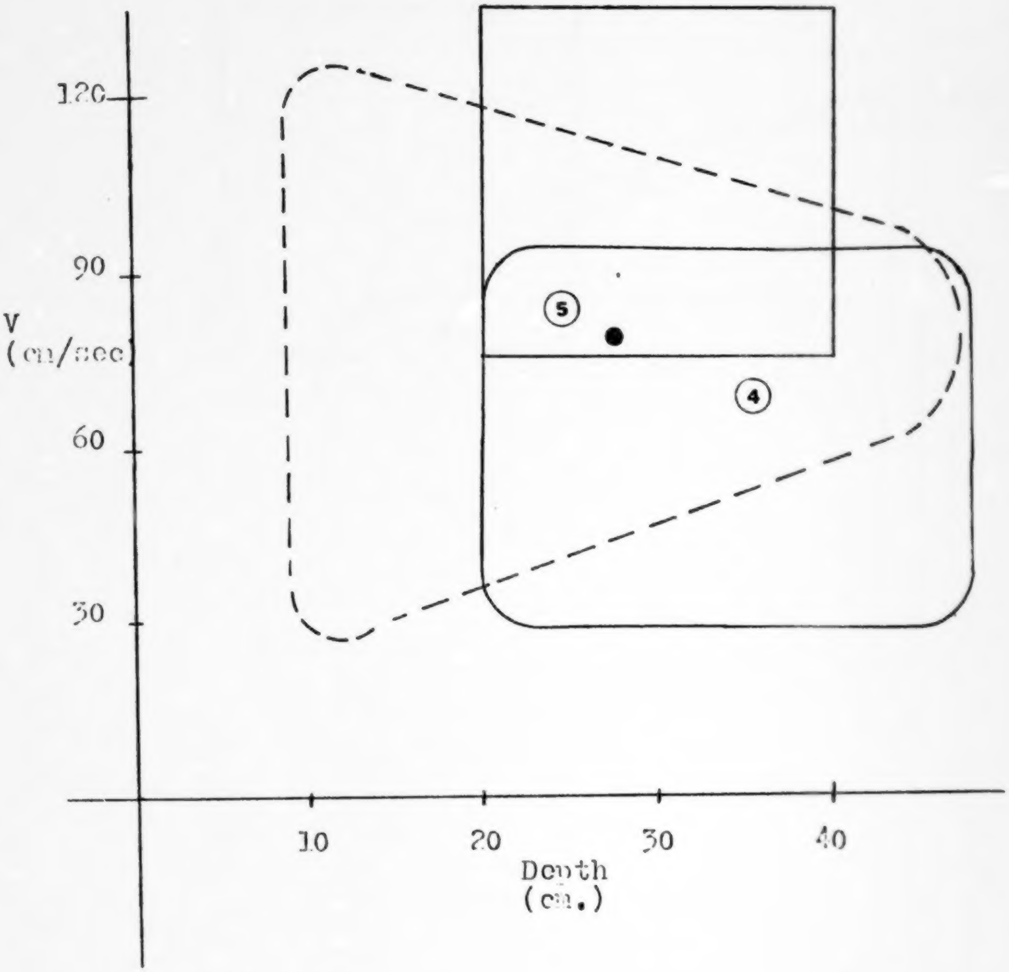

Figure D9. Optimum Depths and Current Velocities. Plecoptera. Isogenoides frontalis (4 and solid line) and Acroneuria abnormis (5 and dashed line).

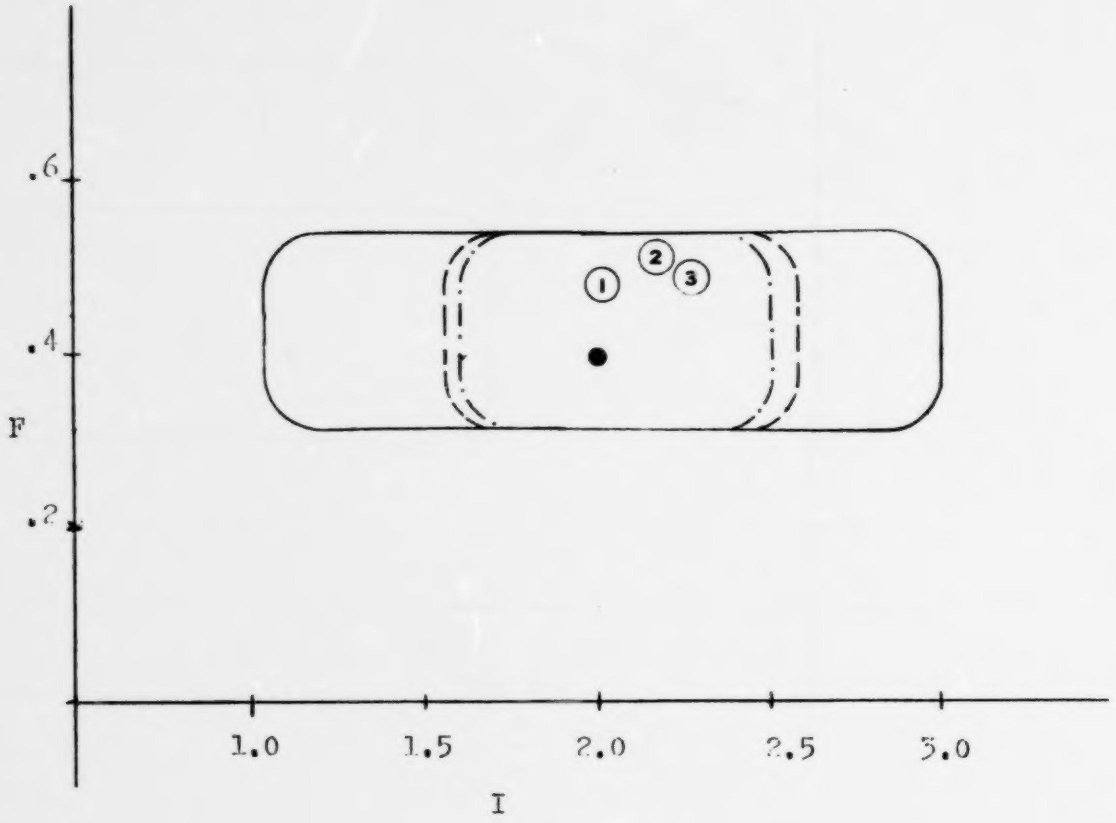

Figure D10. Optimum Turbulence and Microprofile. Plecoptera. Strophopteryx fasciata (1 and solid lines), Paraleuctra sara (2 and dashed line), and Capnia limata (3 and alternating dashed and dotted line).

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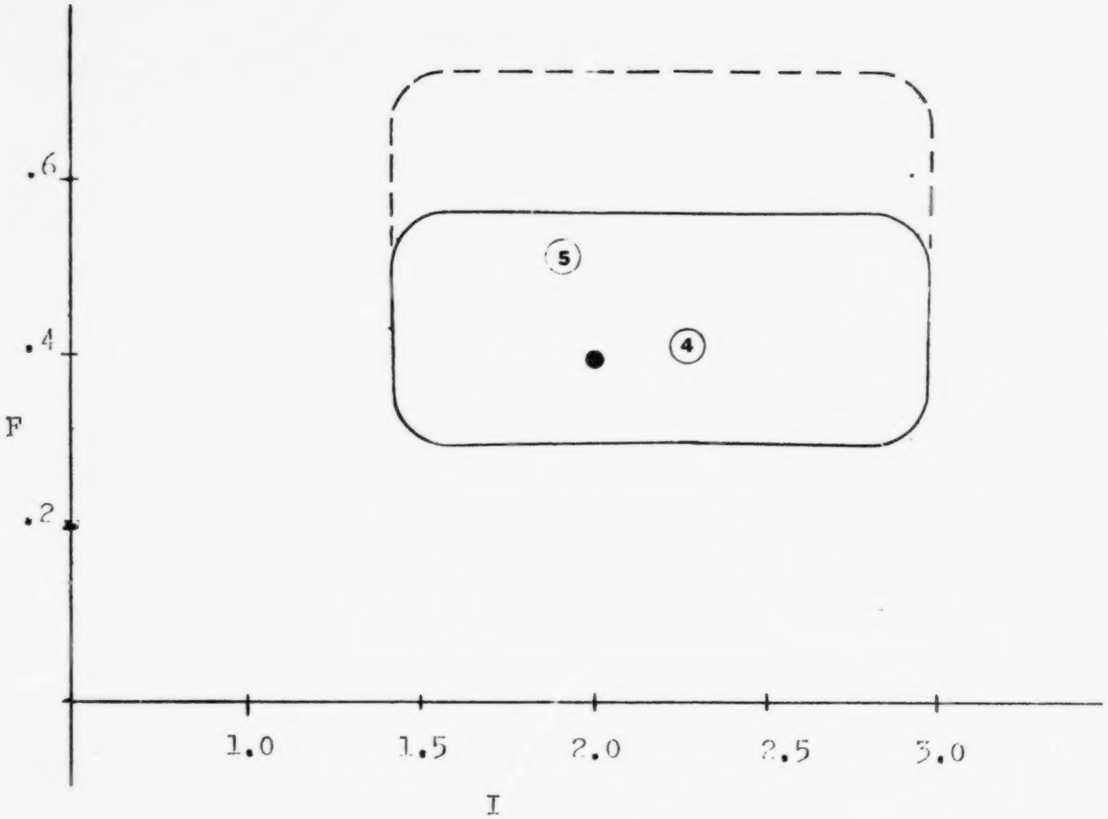


Figure D11. Optimum Turbulence and Microprofile. Plecoptera. Isogenoides frontalis (4 and solid line) and Acroneuria abnormis (5 and dashed line).

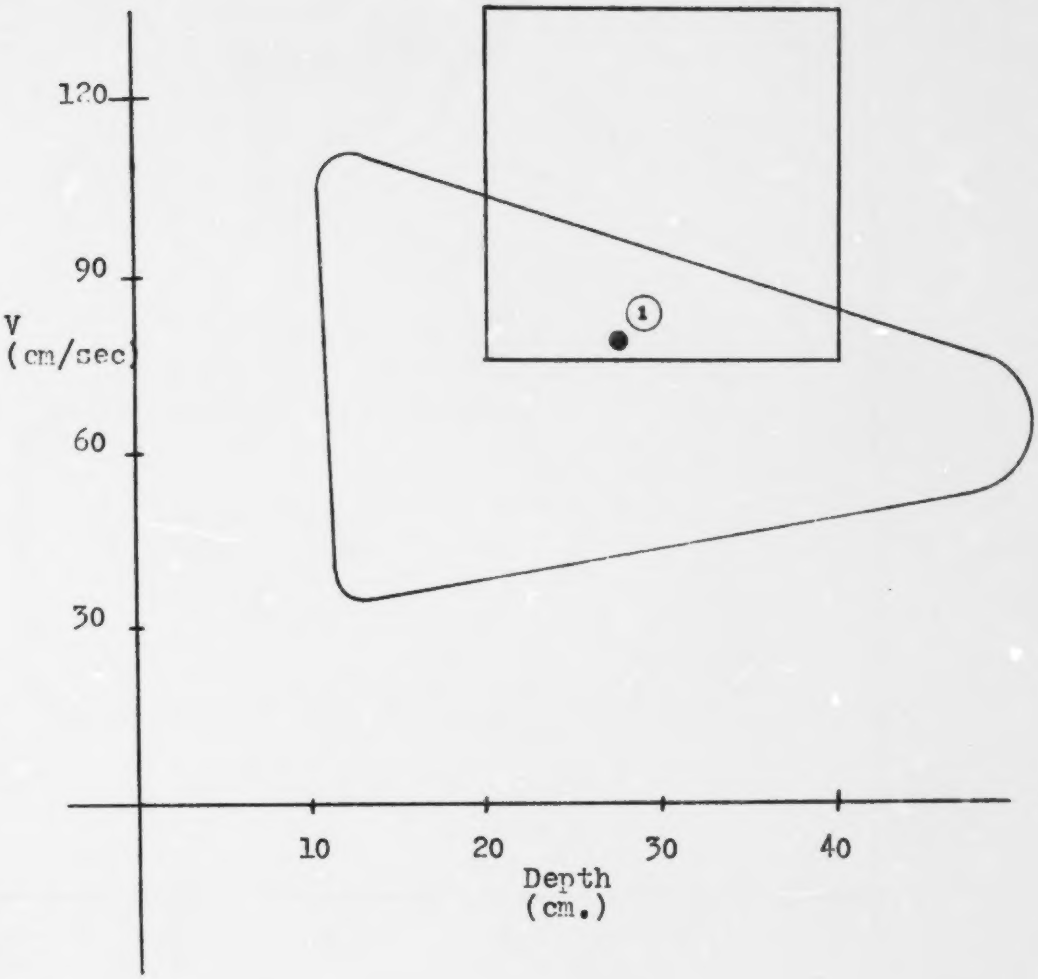


Figure D12. Optimum Depth and Current Velocity. Odonata. Ophiogomphus morrisoni (1 and solid line).

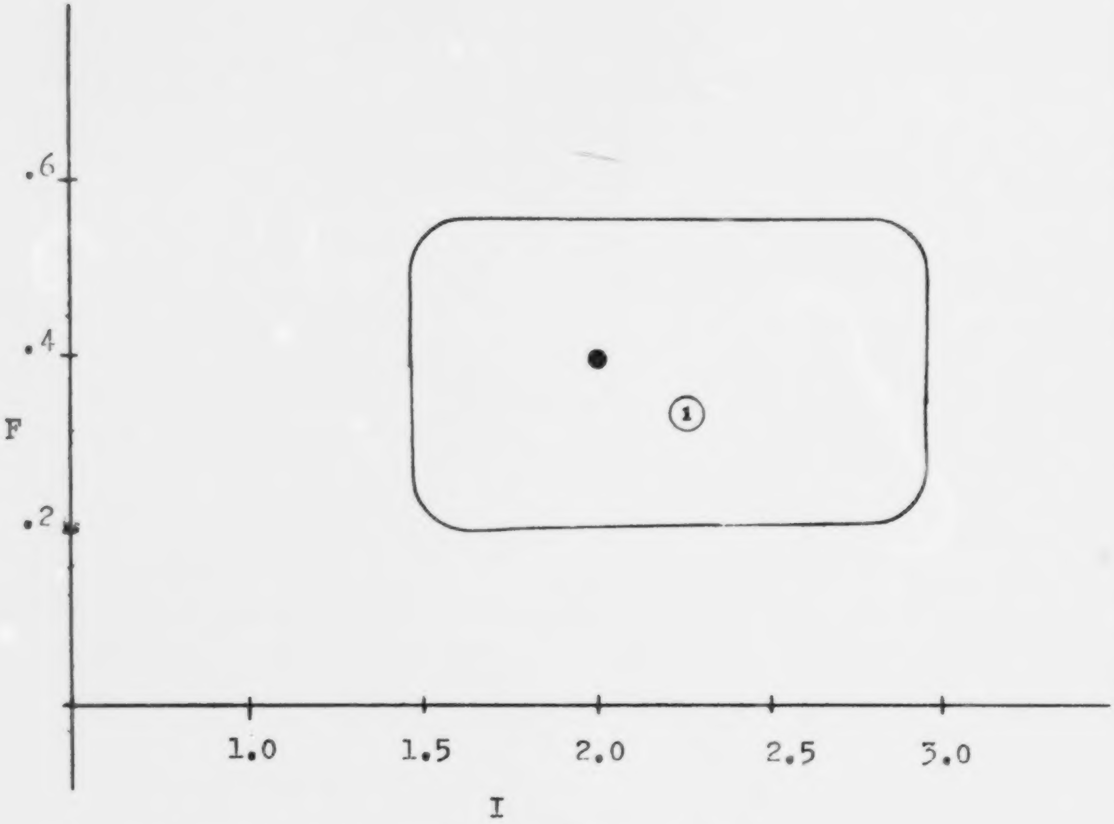


Figure D13. Optimum Turbulence and Microprofile. Odonata. Ophiogomphus morrisoni. (1 and solid line).

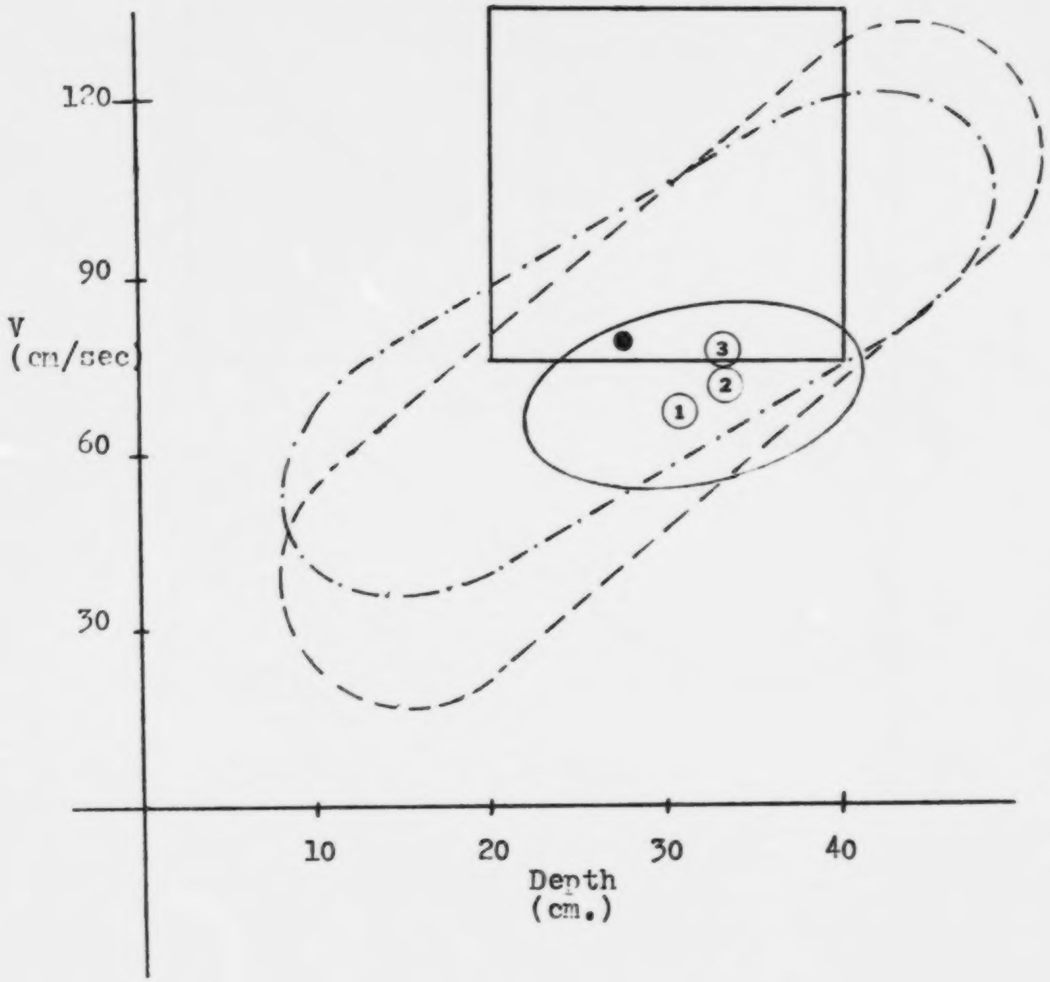


Figure D14. Optimum Depth and Current Velocity. Trichoptera. Hydroptila sp. (1 and solid line), Cheumatopsyche spp. (2 and dashed line), and Hydropsyche bifida (3 and alternating dashed and dotted line).

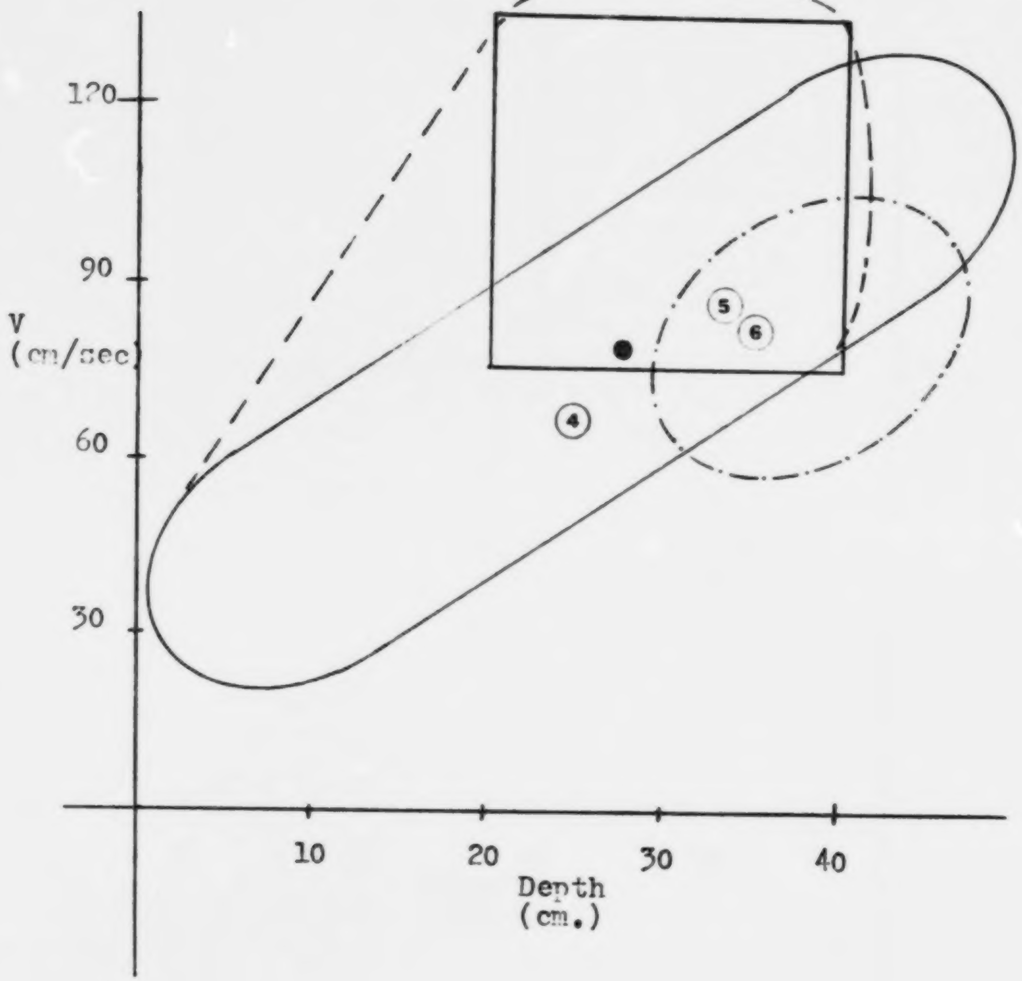


Figure D15. Optimum Depth and Current Velocity. Trichoptera. Hydropsyche occidentalis (4 and solid line), Hydropsyche sp.a (5 and dashed line), and Hydropsyche sp. b (6 and alternating dashed and dotted line).

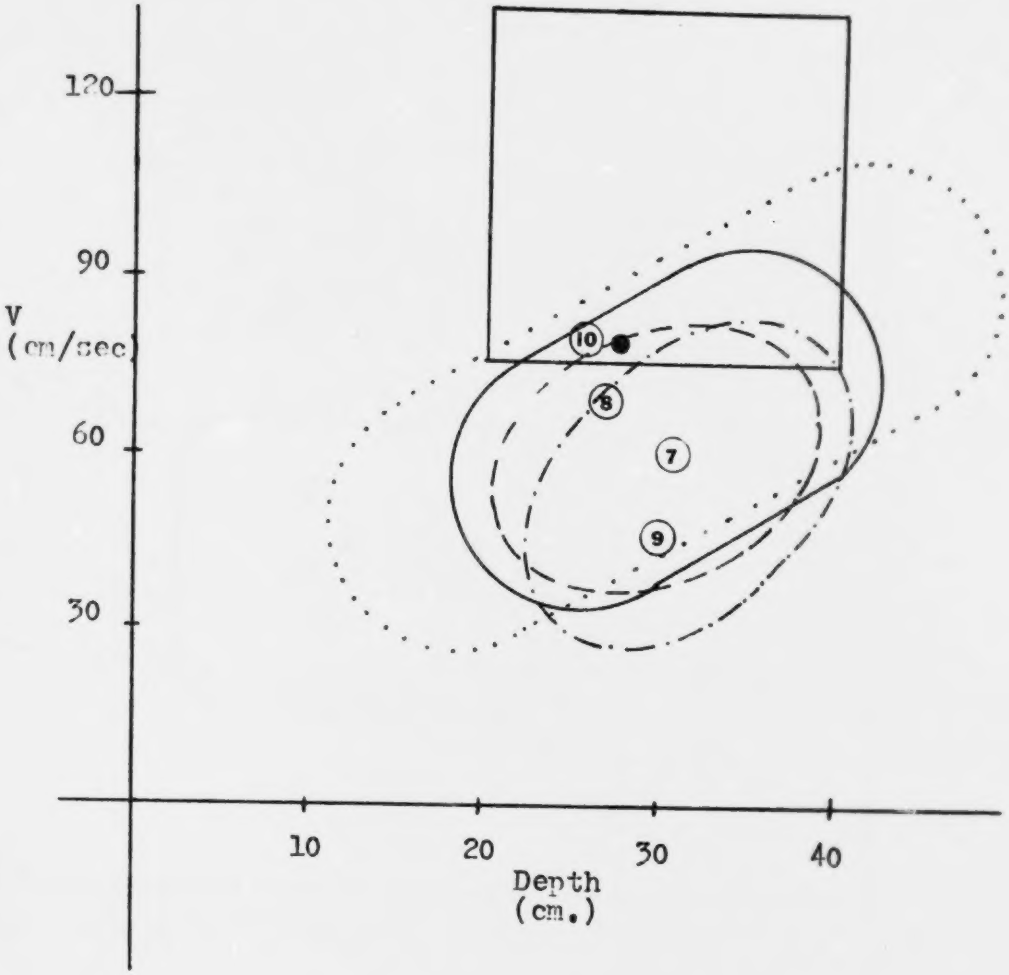


Figure D16. Optimum Depth and Current Velocity. Trichoptera. Hydropsyche sp. c (7 and solid line), Brachycentrus americanus (8 and dashed line), Leptocella sp. (9 and alternating dashed and dotted line), and Athripsodes sp. (10 and dotted line).

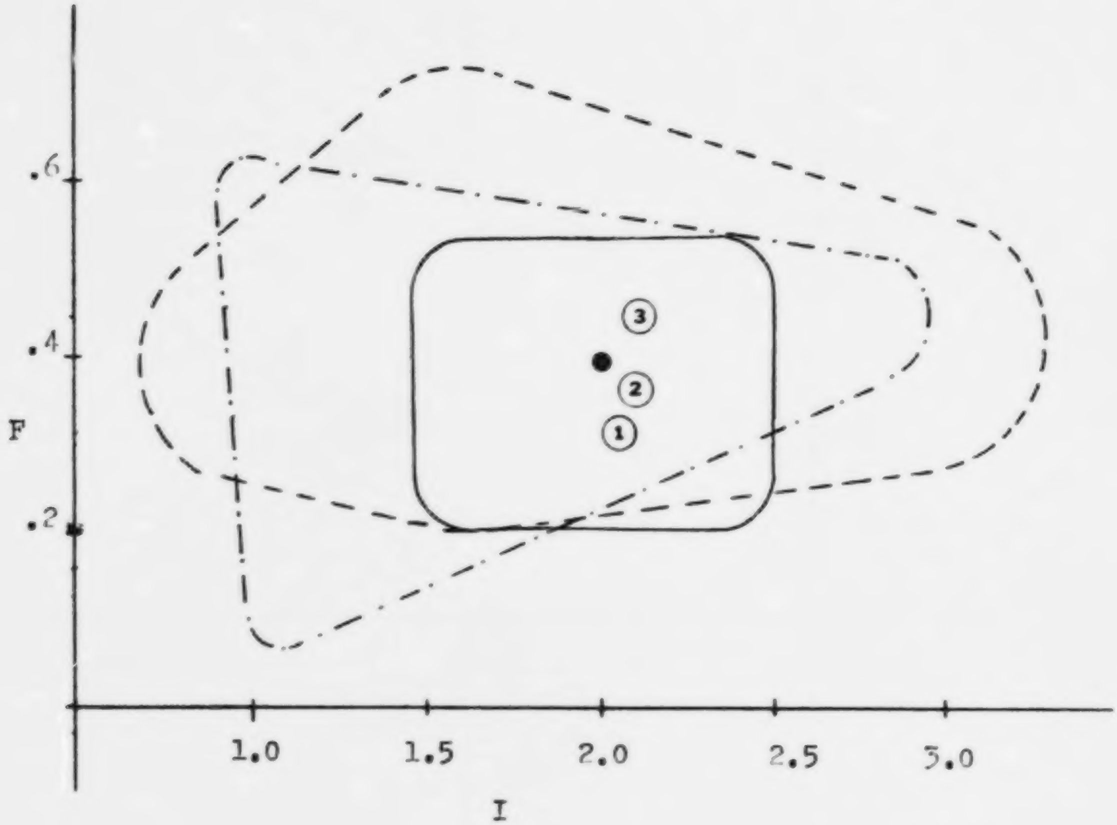


Figure D17. Optimum Turbulence and Microprofile. Trichoptera. Hydroptila sp. (1 and solid line), Cheumatopsyche spp. (2 and dashed line), and Hydropsyche bifida (3 and alternating dashed and dotted line).

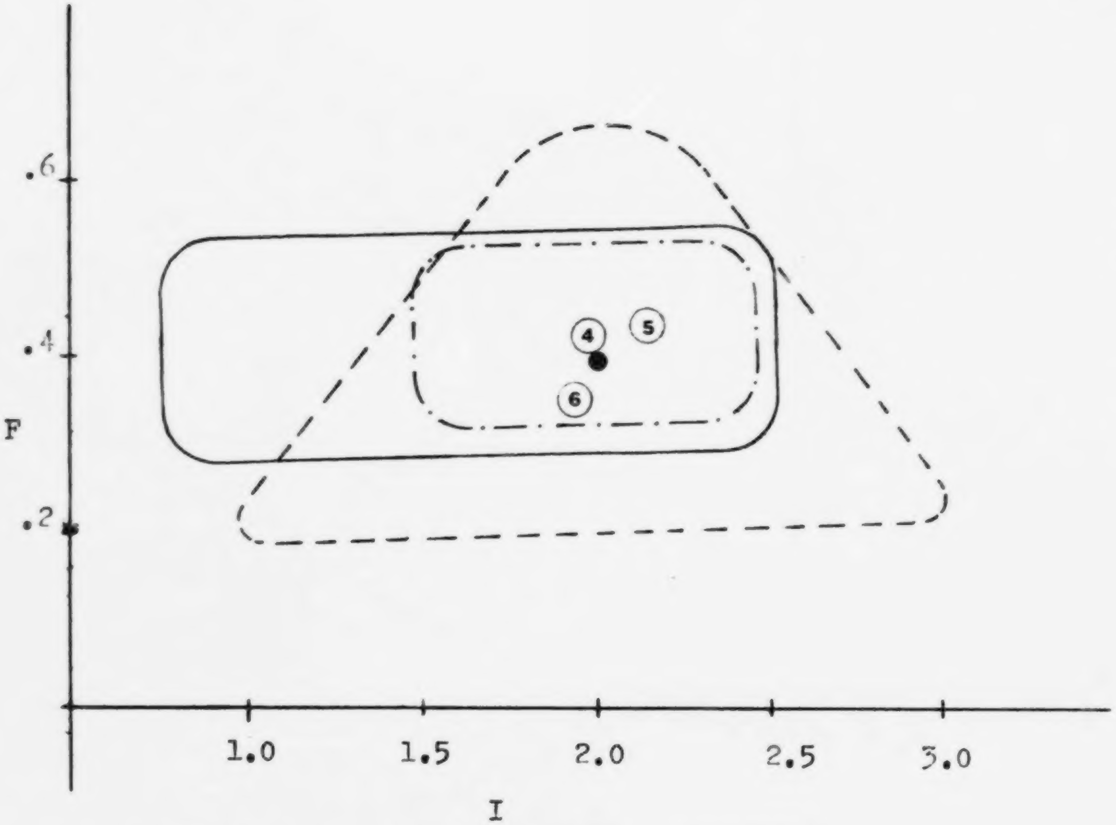


Figure D18. Optimum Turbulence and Microprofile. Trichoptera. Hydropsyche occidentalis (4 and solid line), Hydropsyche sp. a (5 and dashed line), and Hydropsyche sp. b (6 and alternating dashed and dotted line).

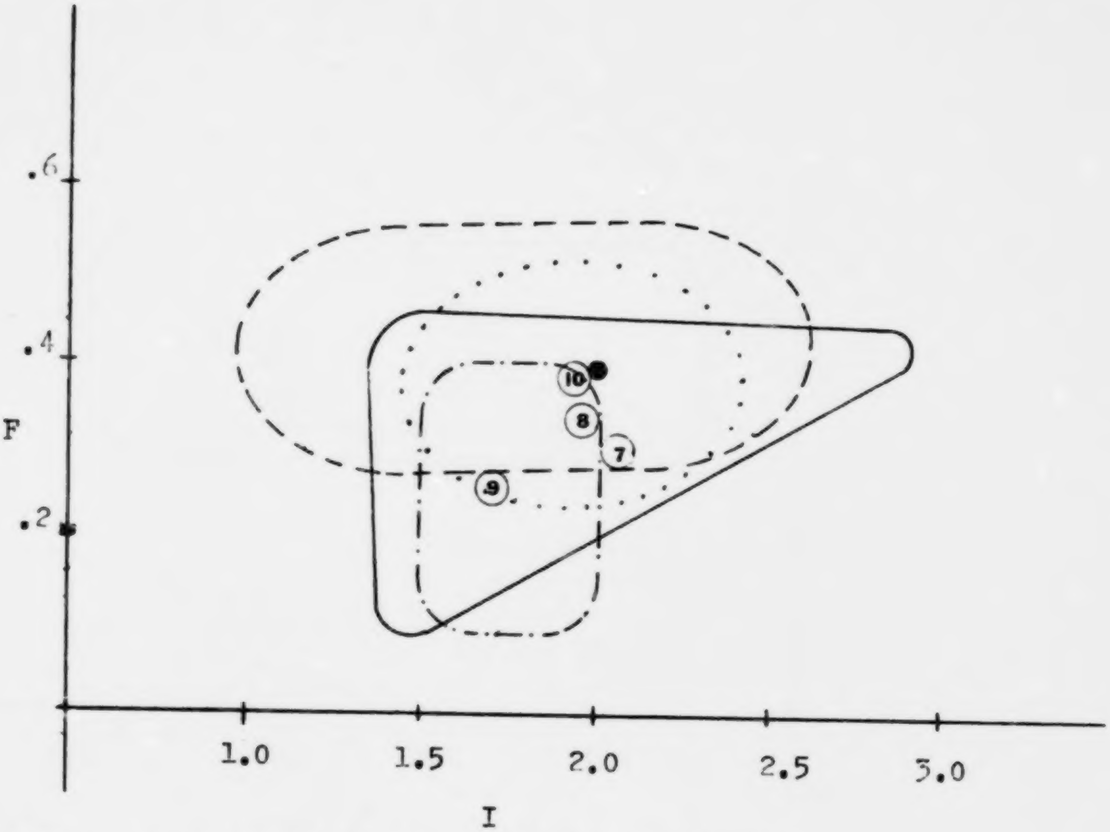


Figure D19. Optimum Turbulence and Microprofile. Trichoptera. Hydropsyche sp. c (7 and solid line), Brachycentrus americanus (8 and dashed line), Leptocella sp. (9 and alternating dashed and dotted line), and Athripsodes sp. (10 and dotted line).

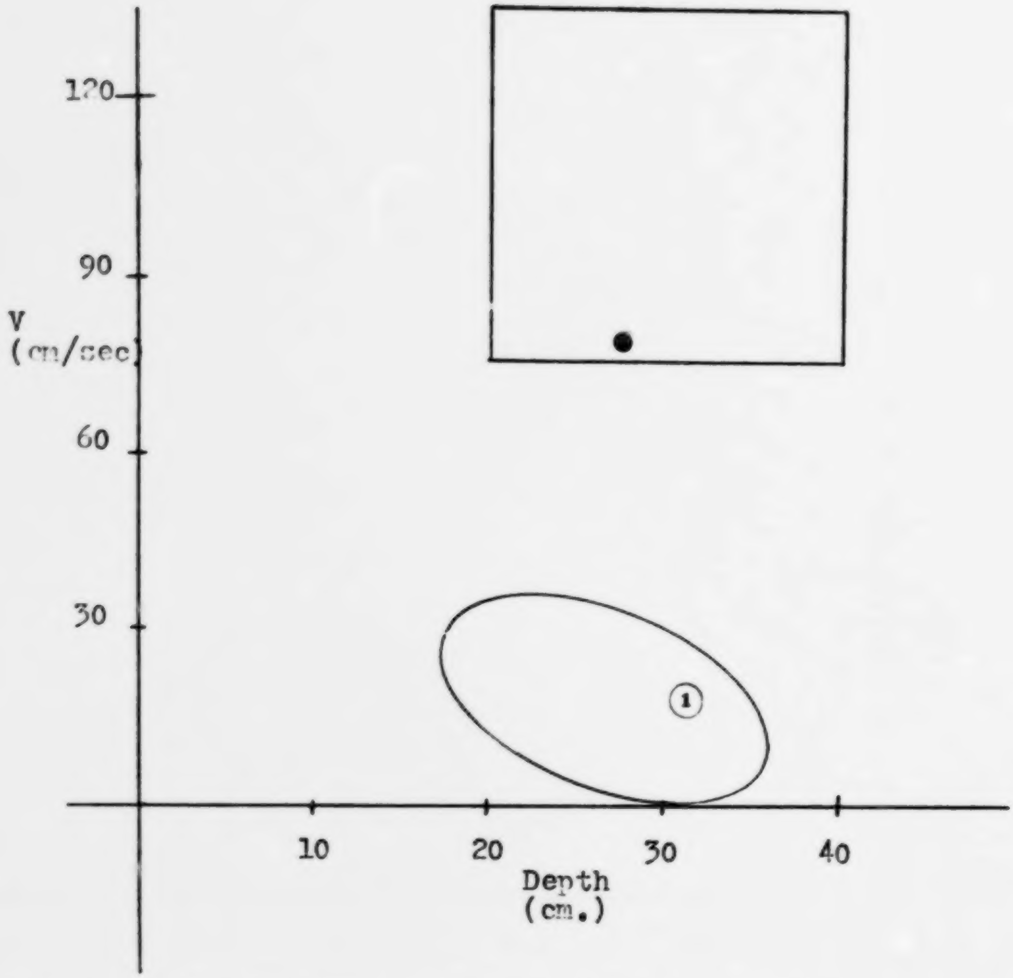


Figure D20. Optimum Depth and Current Velocity. Hemiptera. Rhagovelia sp. (1 and solid line).

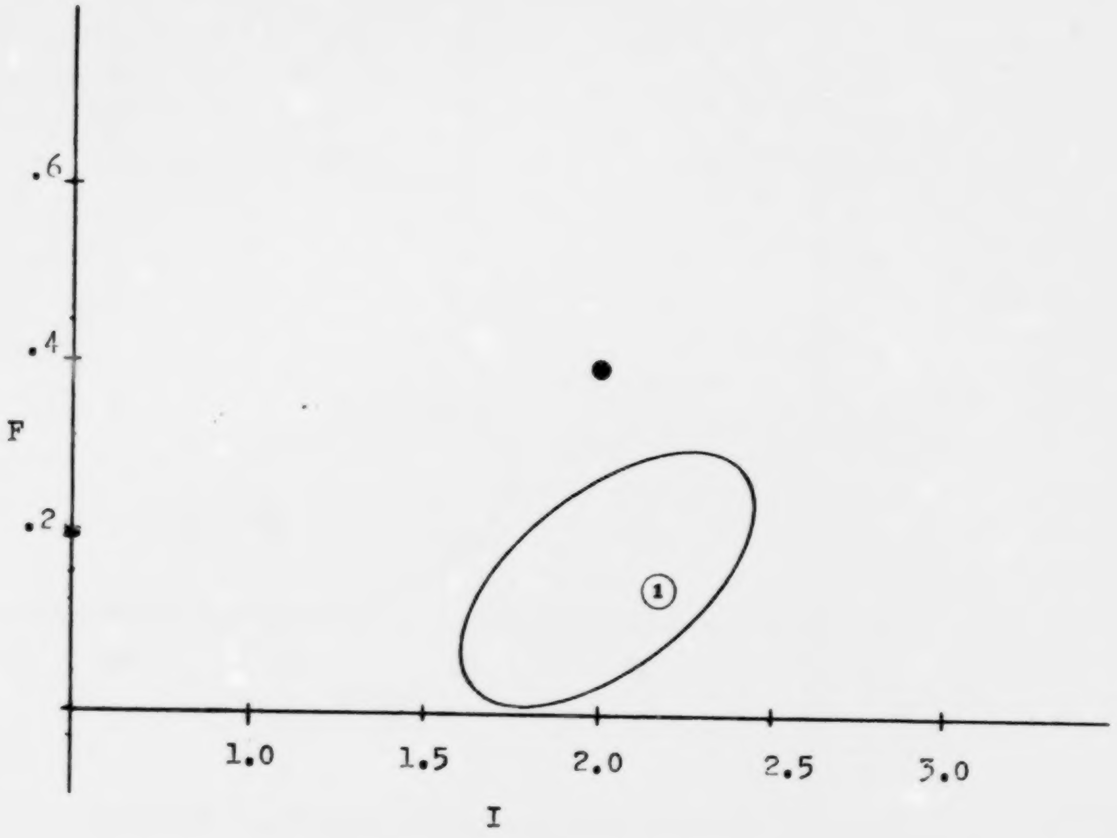


Figure D21. Optimum Turbulence and Microprofile. Hemiptera. Rhagovelia sp. (1 and solid line).

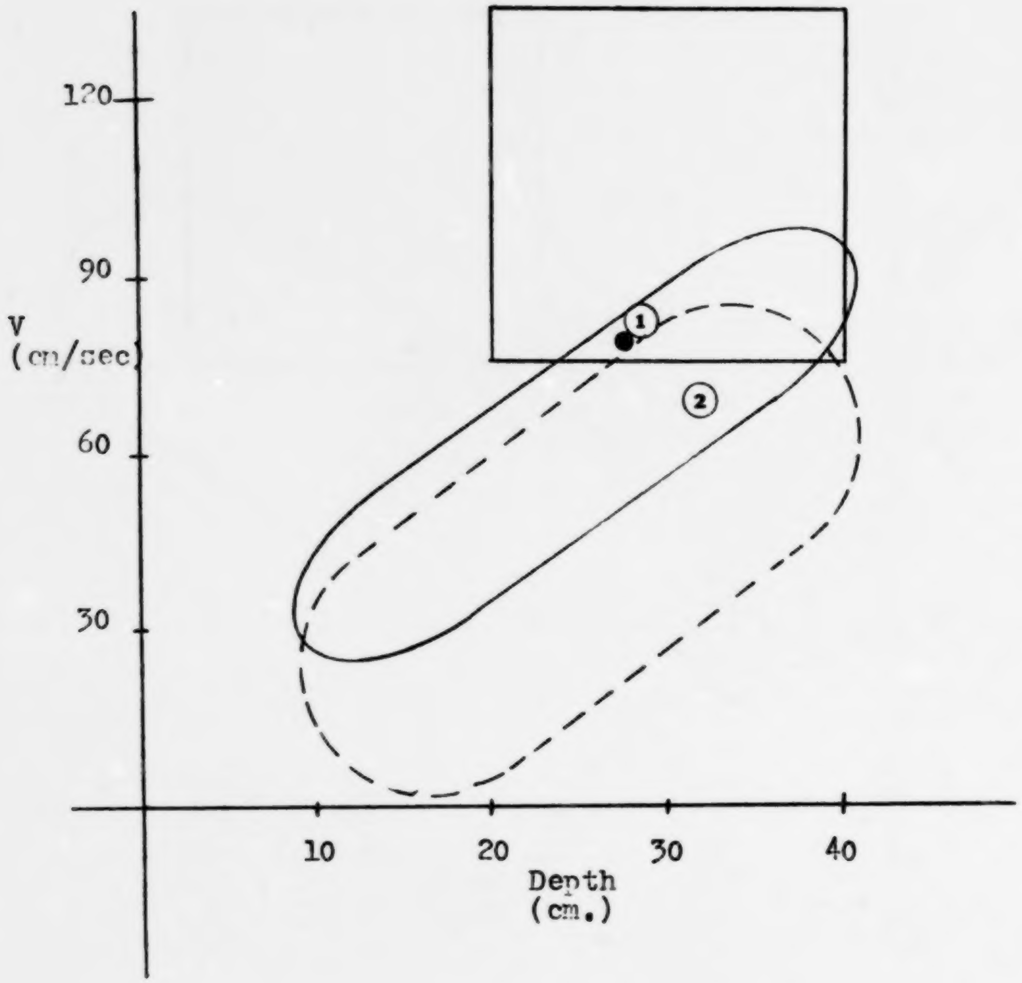


Figure D22. Optimum Depth and Current Velocity. Coleoptera. Stenelmis sp. a (adult) (1 and solid line) and Stenelmis sp. b (adult) (2 and dashed line).

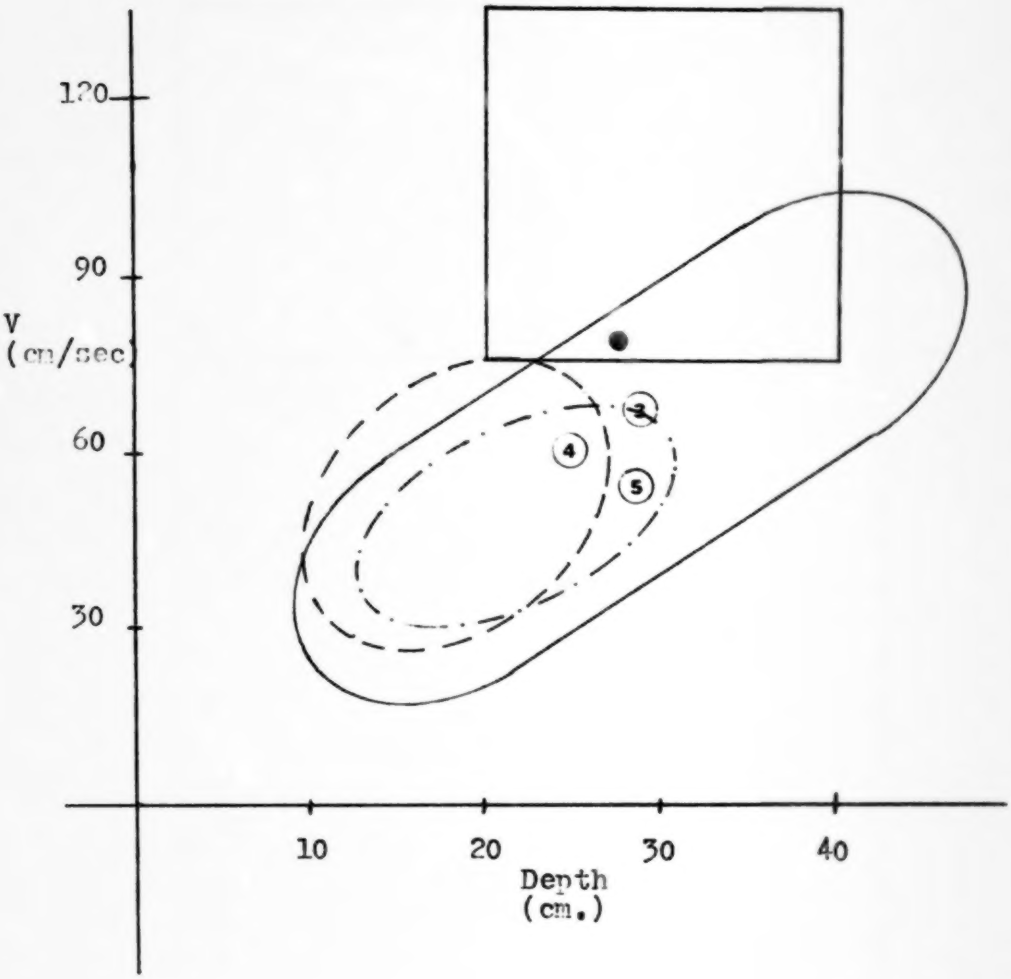


Figure D23. Optimum Depth and Current Velocity. Coleoptera. Stenelmis sp. a (larvae) (1 and solid line), Stenelmis sp. b (larvae) (2 and dashed line), and Dubiraphia sp. (3 and alternating dashed and dotted line).

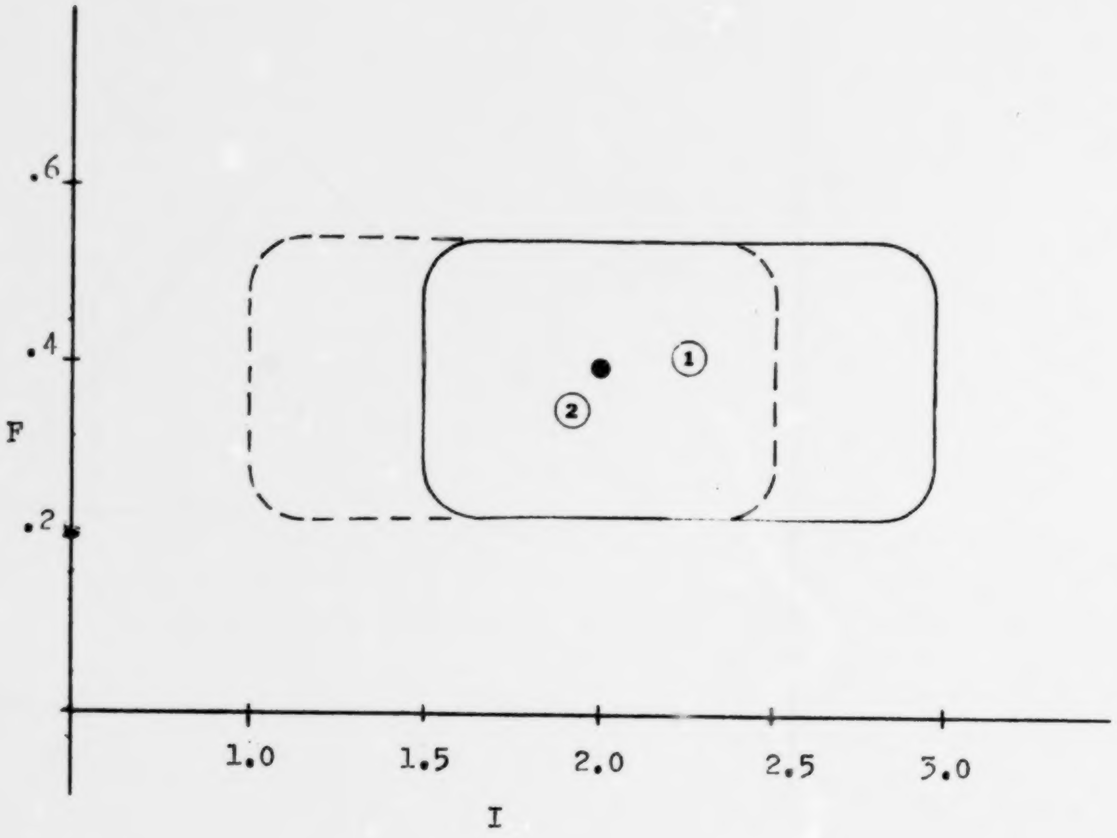


Figure D24. Optimum Turbulence and Microprofile. Coleoptera. Stenelmis sp. a (adult) (1 and solid line) and Stenelmis sp. b (adult) (2 and dashed line).

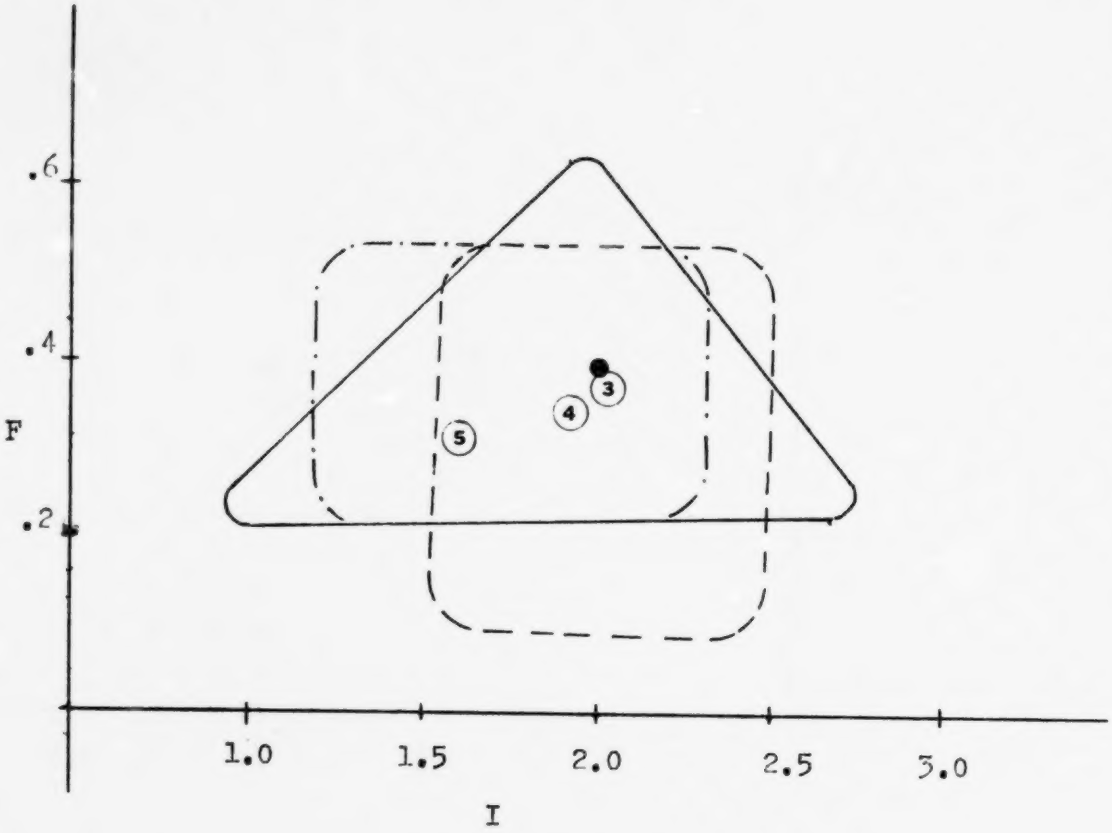


Figure D25. Optimum Turbulence and Microprofile. Coleoptera. Stenelmis sp. a (larvae)(1 and solid line), Stenelmis sp. b (larvae)(2 and dashed line), and Dubiraphia sp. (3 and alternating dashed and dotted line).

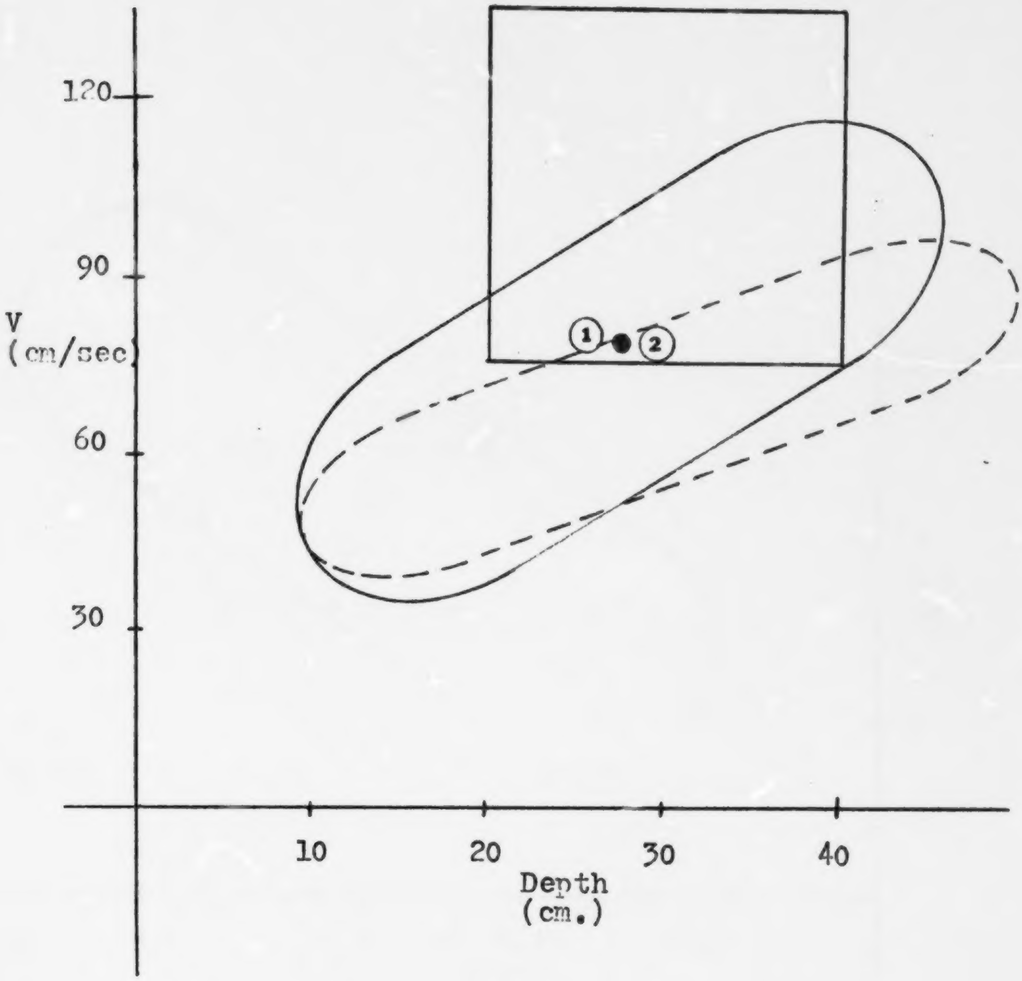


Figure D26, Optimum Depth and Current Velocity. Diptera. Simulium spp. (1 and solid line) and Metriocnemus sp. (2 and dashed line).

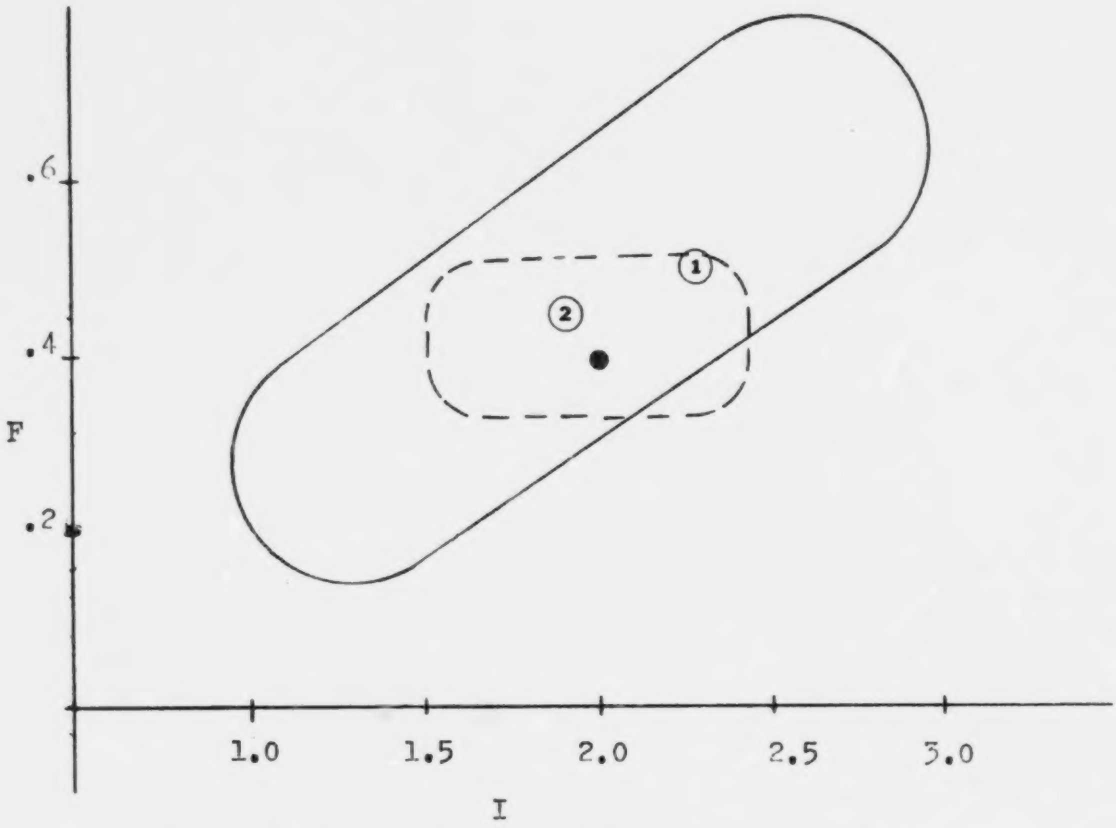


Figure D27. Optimum Turbulence and Microprofile. Diptera. Simulium spp. (1 and solid line) and Metriocnemus sp. (2 and dashed line).

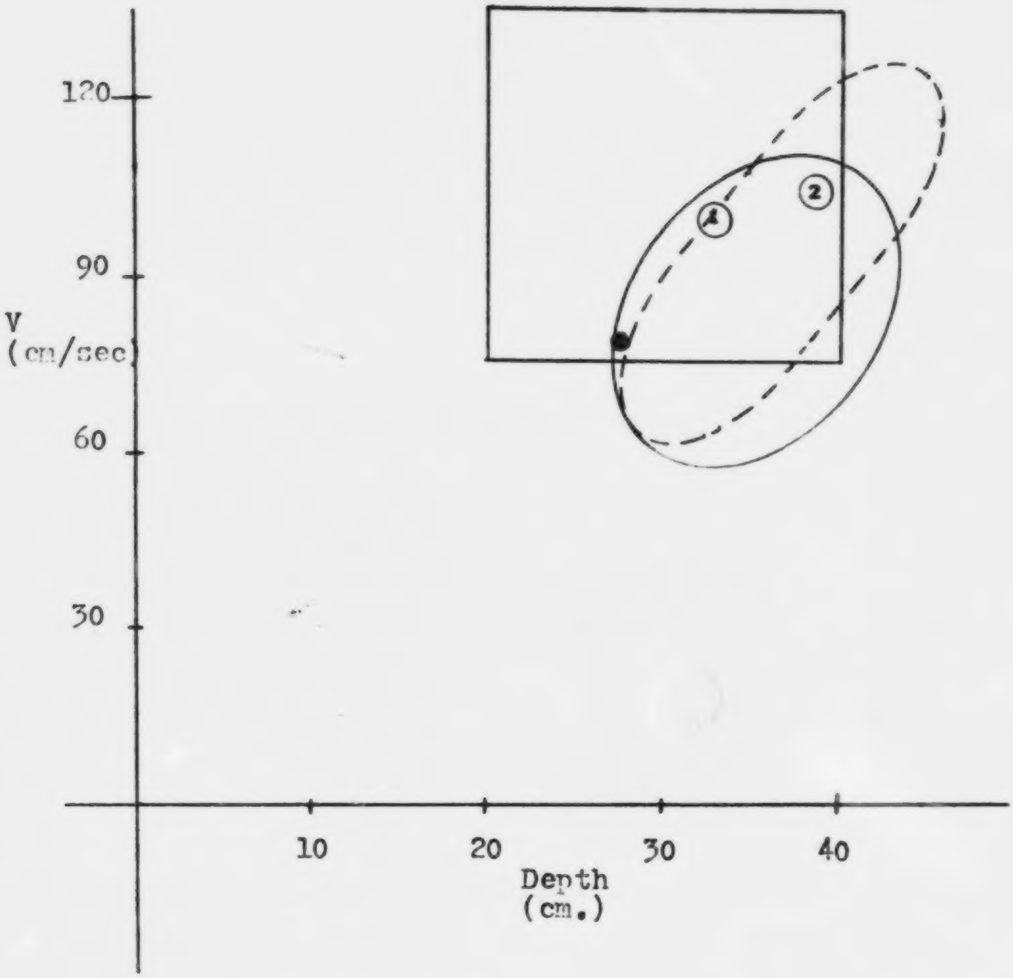


Figure D28. Optimum Dept and Current Velocity. Mollusca. Sphaerium simile (1 and solid line) and Physa gyrina (2 and dashed line).

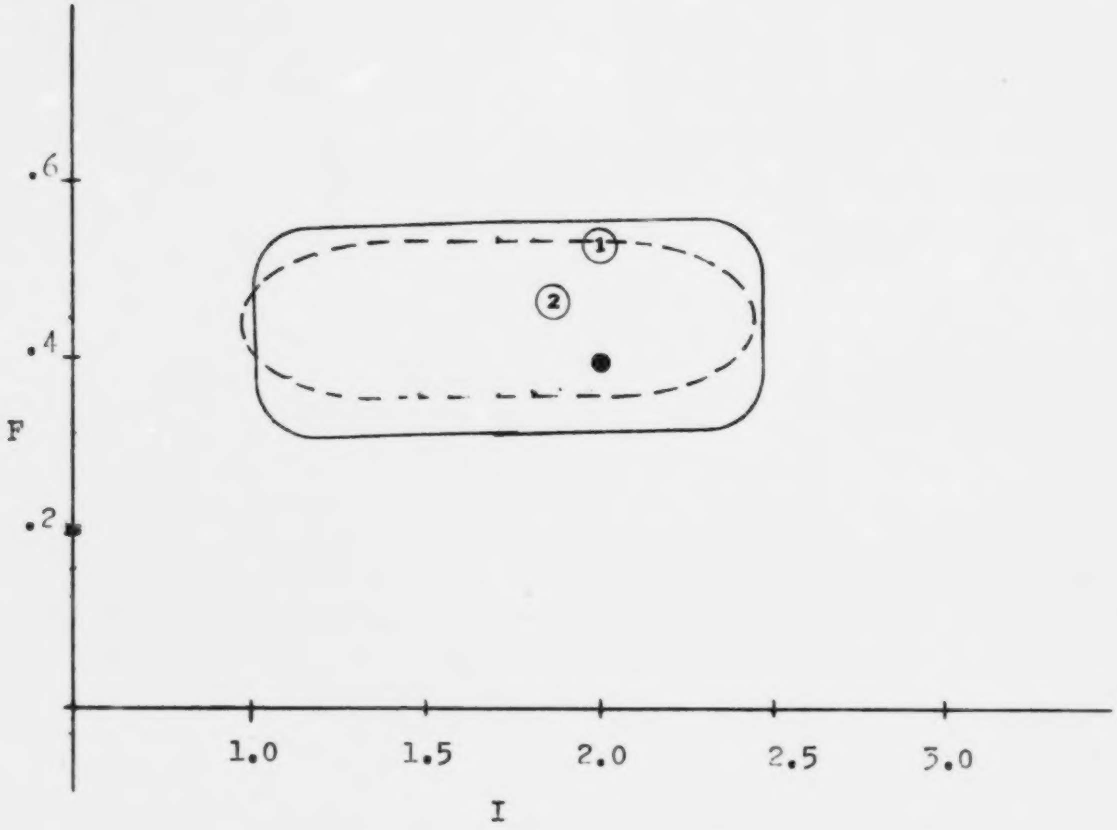


Figure D29. Optimum Turbulence and Microprofile. Mollusca. Sphaerium simile (1 and solid line) and Physa gyrina (2 and dashed line).

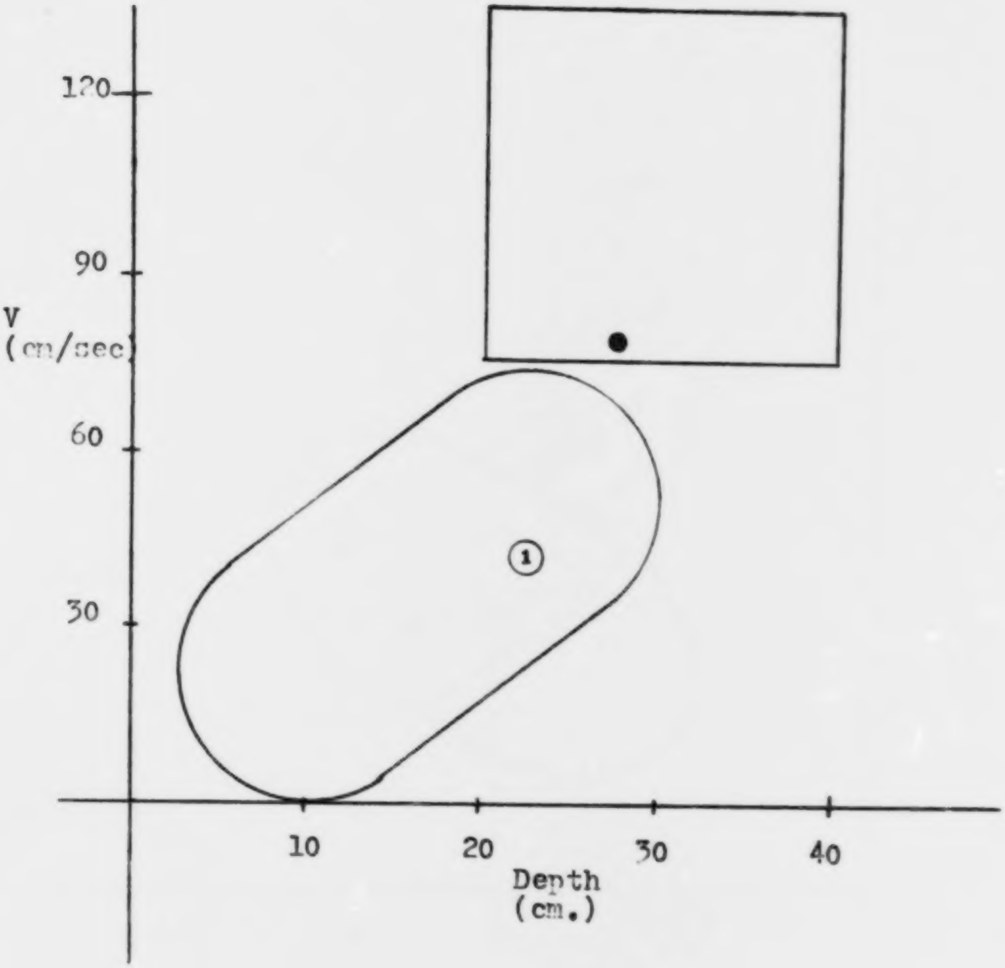


Figure D30. Optimum Depth and Current Velocity. Turbellaria. Dugesia tigrina (1 and solid line).

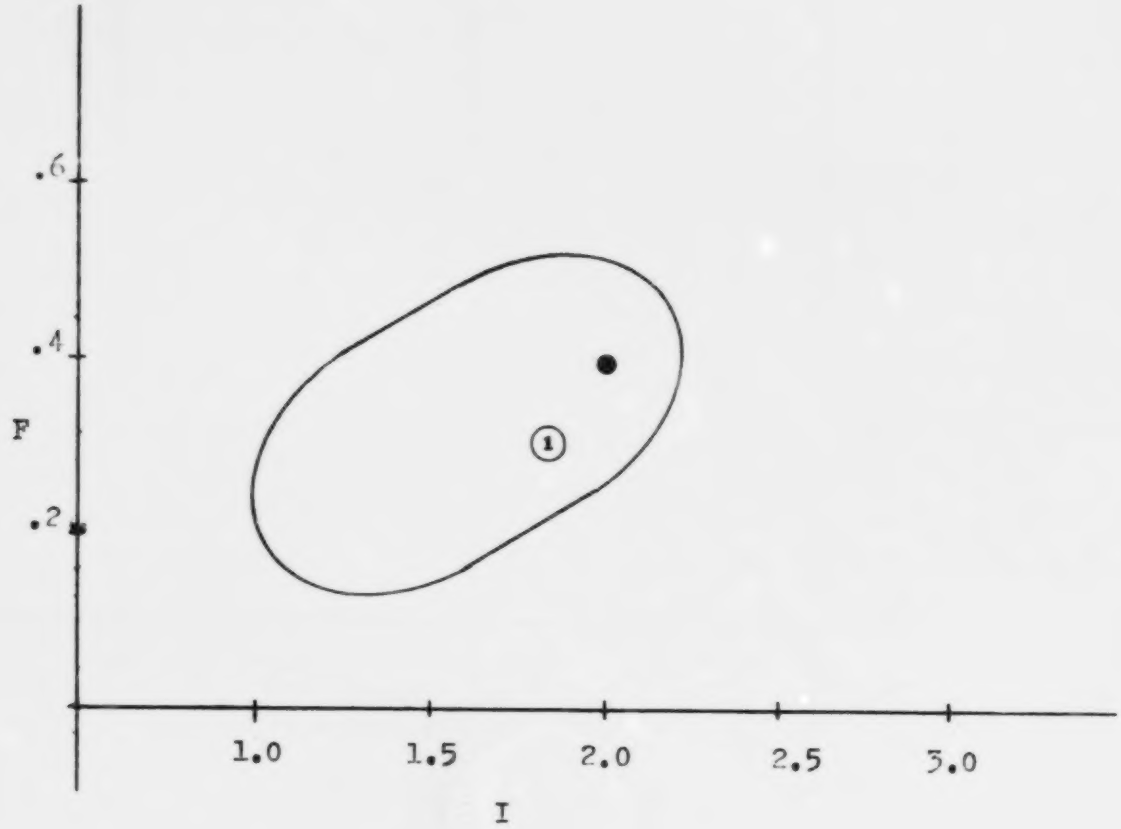


Figure D31. Optimum Turbulence and Microprofile. Turbellaria. Dugesia tigrina (1 and solid line).

Distribution and Abundance

Kite-diagrams (Figures D34 and D35) are presented showing relative abundance and longitudinal distribution along the Tongue River (Figure D32, Table D4). Dashed lines indicate the presence of the organism in that section of the river, as determined by kick samples, for which relative abundances have not been determined.

Analysis of the kite-diagrams to determine community associations can be accomplished through the use of clustering techniques. A modified Jaccard association coefficient (Church, 1976) is used to compare community structures, as determined by Hess samples for distributional information. An association matrix is constructed where the association values are determined as follows:

$$J_{ij} = P_i \times P_j \qquad \text{(Eq. D2)}$$

where

$$P_i = (a + b)/(a + b + c) \qquad \text{(Eq. D3)}$$

and

$$P_j = (a + c)/(a + b + c) \qquad \text{(Eq. D4)}$$

when a is the sum of the relative abundances of those species which occur in both samples i and j, b is the sum of the relative abundances of those species which occur only in sample i, and c is the sum of the relative abundances of species which occur only in sample j.

Dendrograms (Figures D33) are constructed by using the WPGMA (weighted pair-group using mathematical averages) clustering method (Sneath and Sokal, 1974). The dendrogram indicates those samples which are most closely related (that is, most similar) by connecting them together at the highest possible association coefficient. Coefficients range from 0 to 1, where 1 is identity. Thus, for example, in the fall-winter distribution, samples III' and III are virtually identical with an association coefficient of .974. It is for this reason that sample site III' was eliminated from further consideration in subsequent logitudinal sampling. The high degree of similarity of community structure indicates that the effects of the sewage effluent in the town of Birney is small enough so that samples taken at site III would be representative of the aquatic community of the general area.

From the dendrogram of the fall-winter distribution (Figure D33), it can be seen that three distinct communities exist along the length of the Tongue River. Sites I and II are in the cold water section and association with communities in the warm water section is very small (.475). In the upper warm water area a distinct community exists, as shown by samples III' and III, and IV. Sample V seems transitional between the upper and lower warm water communities, and as such, is not closely associated with either. It does, however, seem to be most closely associated with the upper warm water community. The lower river shows a third distinct community. In this area, the close association between sites VI and VII, with such different substrates (Table D4) indicates the preference of the insects in these areas for a distinct profile (tending to be smooth) rather than a substrate material type. Turbidity and algal cover seem to be variables which may also cause close association of these two communities.

It can be seen that the transition zone between cold water and warm water habitats (as delineated in Figures D33 and D34, and by sample III') serves as the border for the upstream distribution of many organisms. Only a few insect genera (Baetis, Strophopteryx, Hydropsyche, Simulium, and Metriocnemus) extend the entire length of the river, through both cold and warm water environments.

The Effect of Hypolimnial Discharge:

Neel (1963) states that if a reservoir is deep enough to become thermally stratified and has a hypolimnial drain, the discharge of cold water has a stabilizing effect on the thermal regime of the river below the dam, such that temperatures are considerably colder in the summer and warmer in the winter. Hubbs (1972) has found that the reduction of 24-hour temperature fluctuations

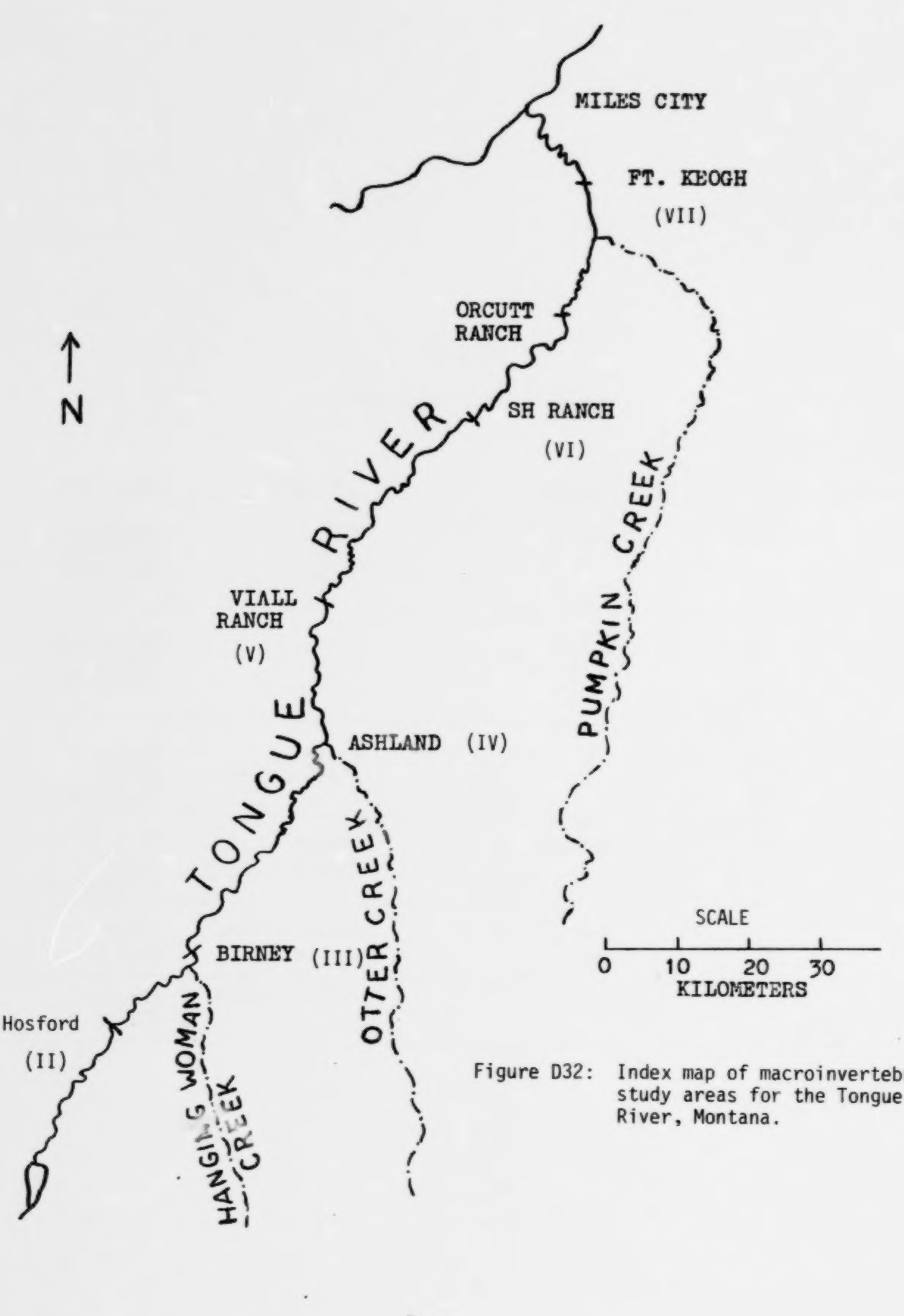


Figure D32: Index map of macroinvertebrate study areas for the Tongue River, Montana.

TABLE D4

Collection Area Characteristics

AREA	TURBIDITY	SUBSTRATE	PERIPHYTON
I II	Low	Medium to large cobble	*Cladophora*, *Spirogyra*, dense mats
III' III	Low to moderate	Medium to large cobble	*Cladophora*, *Spirogyra*, sparse mats
IV	Low	Medium to small cobble	*Mostoc*, sparse Cladophora
V	Moderate	Medium cobble	*Mostoc*, sparse Cladophora
VI	Moderate to Heavy	Bedrock with medium cobble	Heavy *Nostoc*
VII	Heavy	Medium cobble and sand	Heavy *Nostoc*

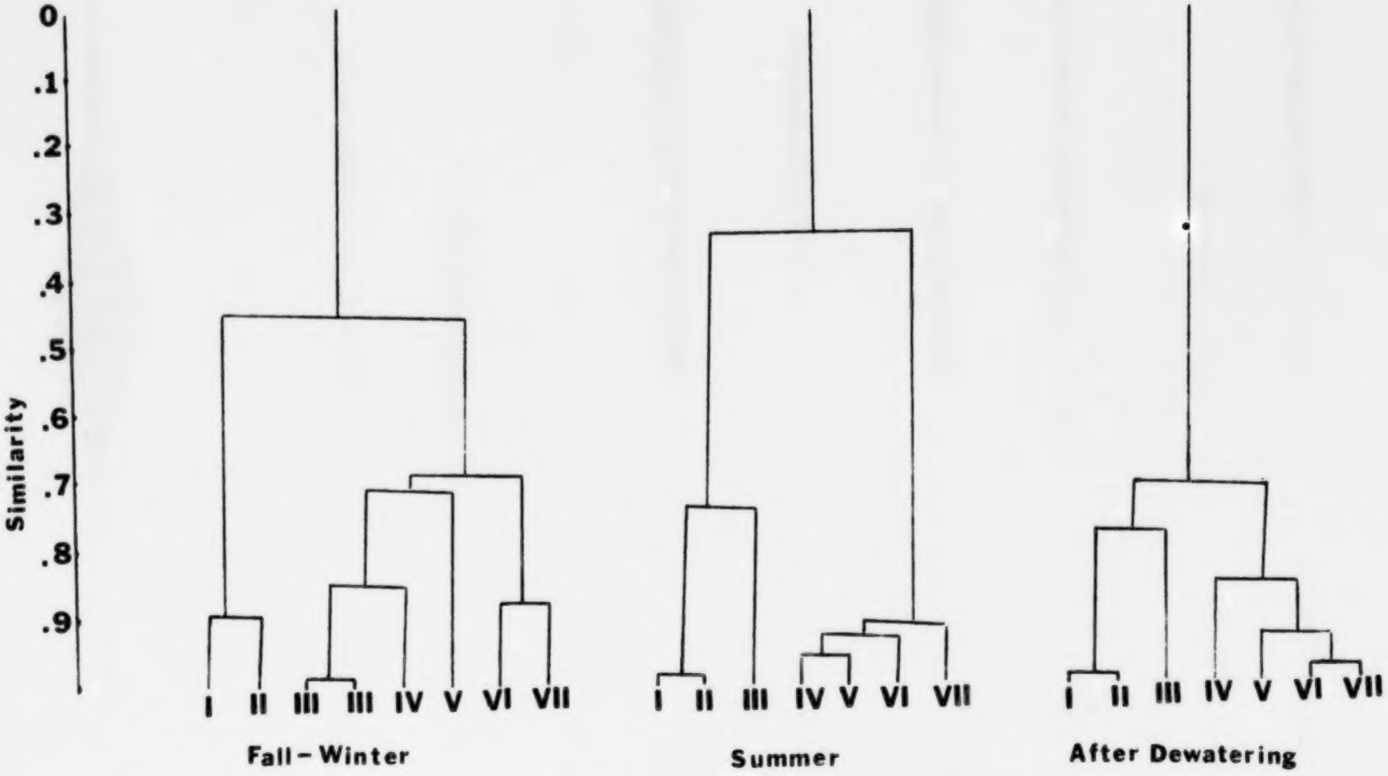


Figure D33. Association Dendrograms. See text for details.

Figure D34. Fall-Winter Benthic Macroinvertebrate Abundances.

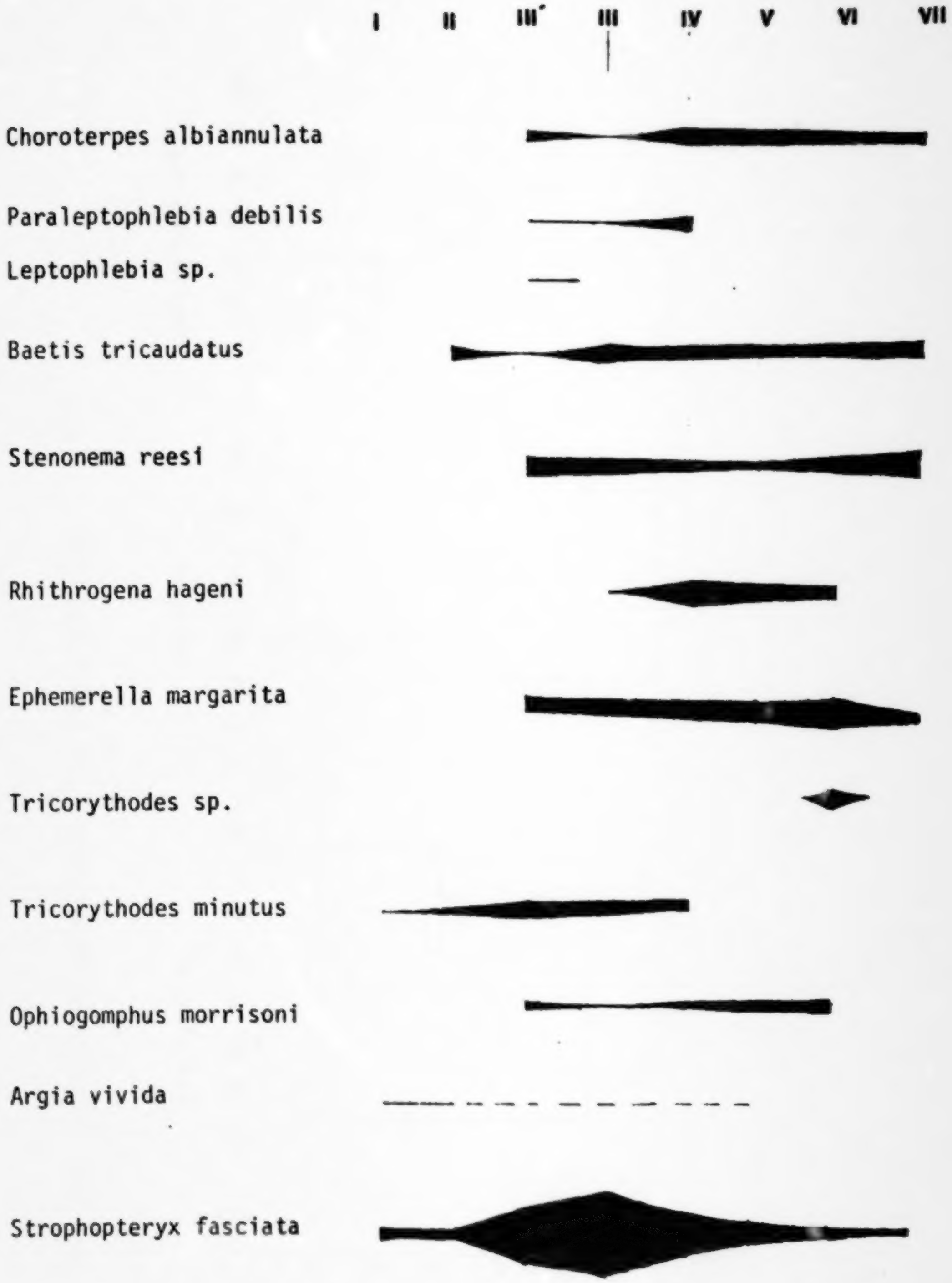


Figure D34 (cont.)

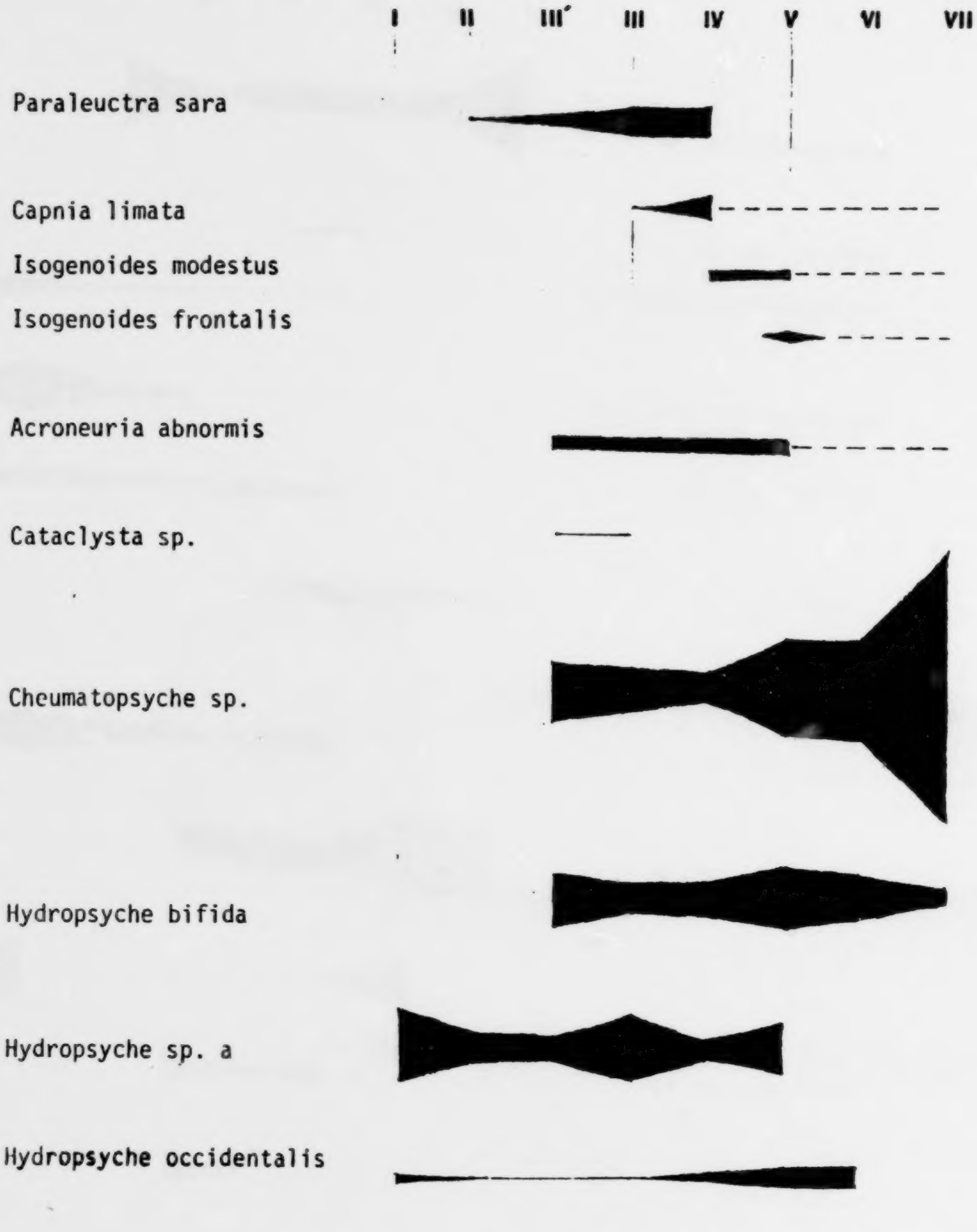


Figure D34 (cont.)

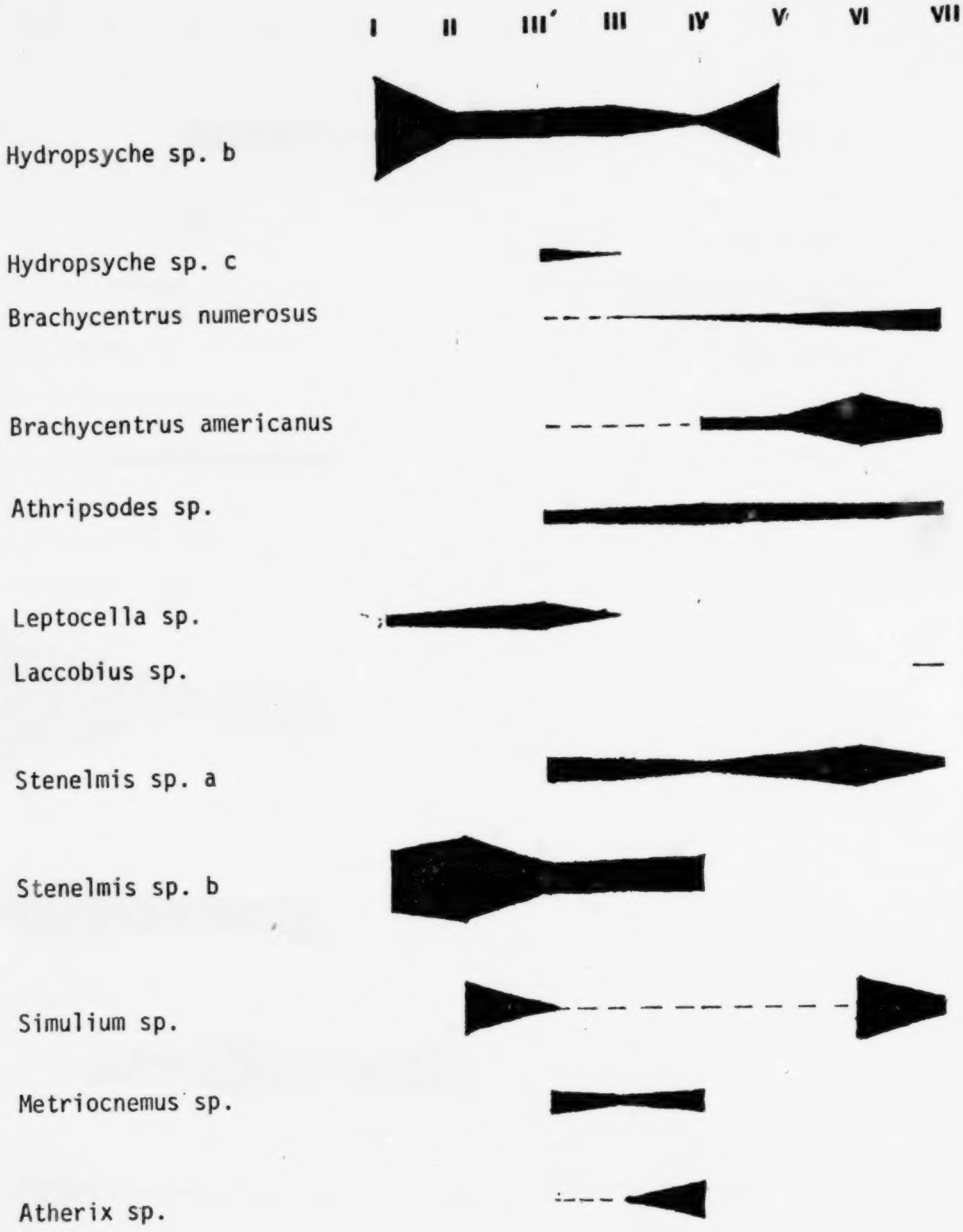


Figure D34 (cont.)

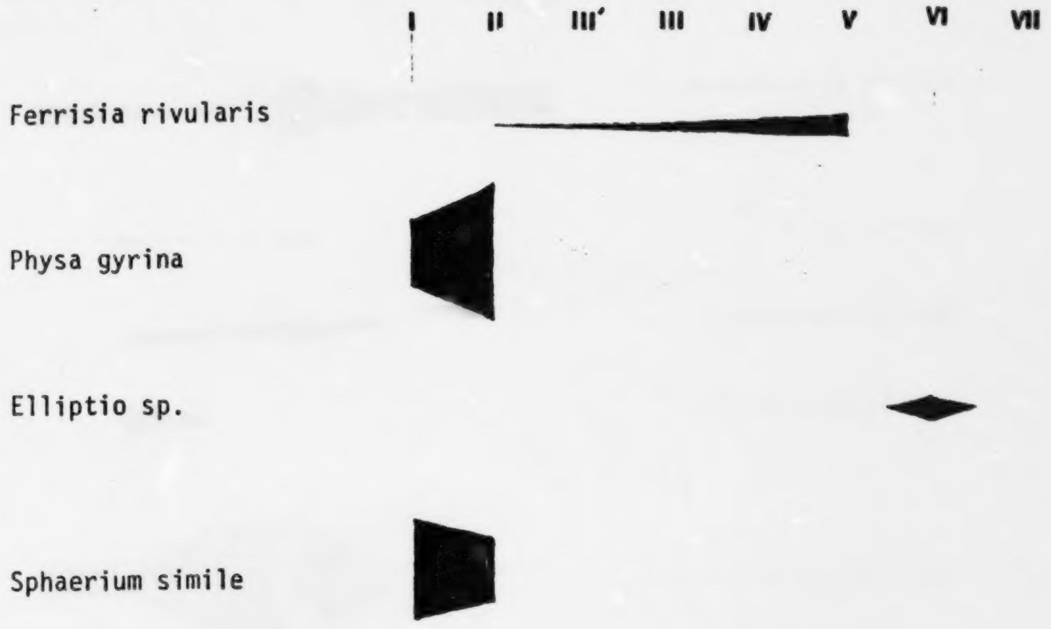


Figure D35. Summer Benthic Macroinvertebrate Abundances.

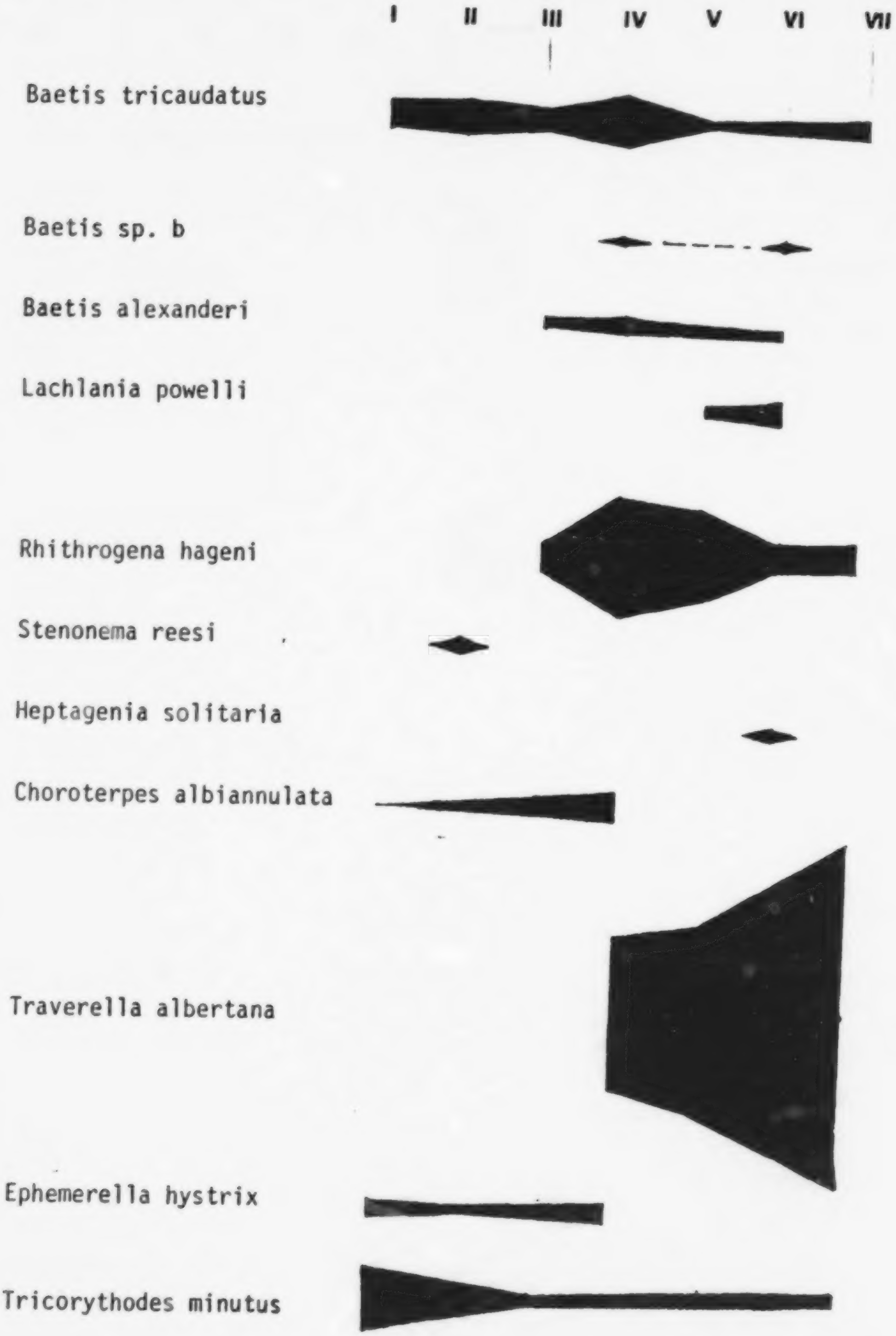


Figure D35 (cont.)

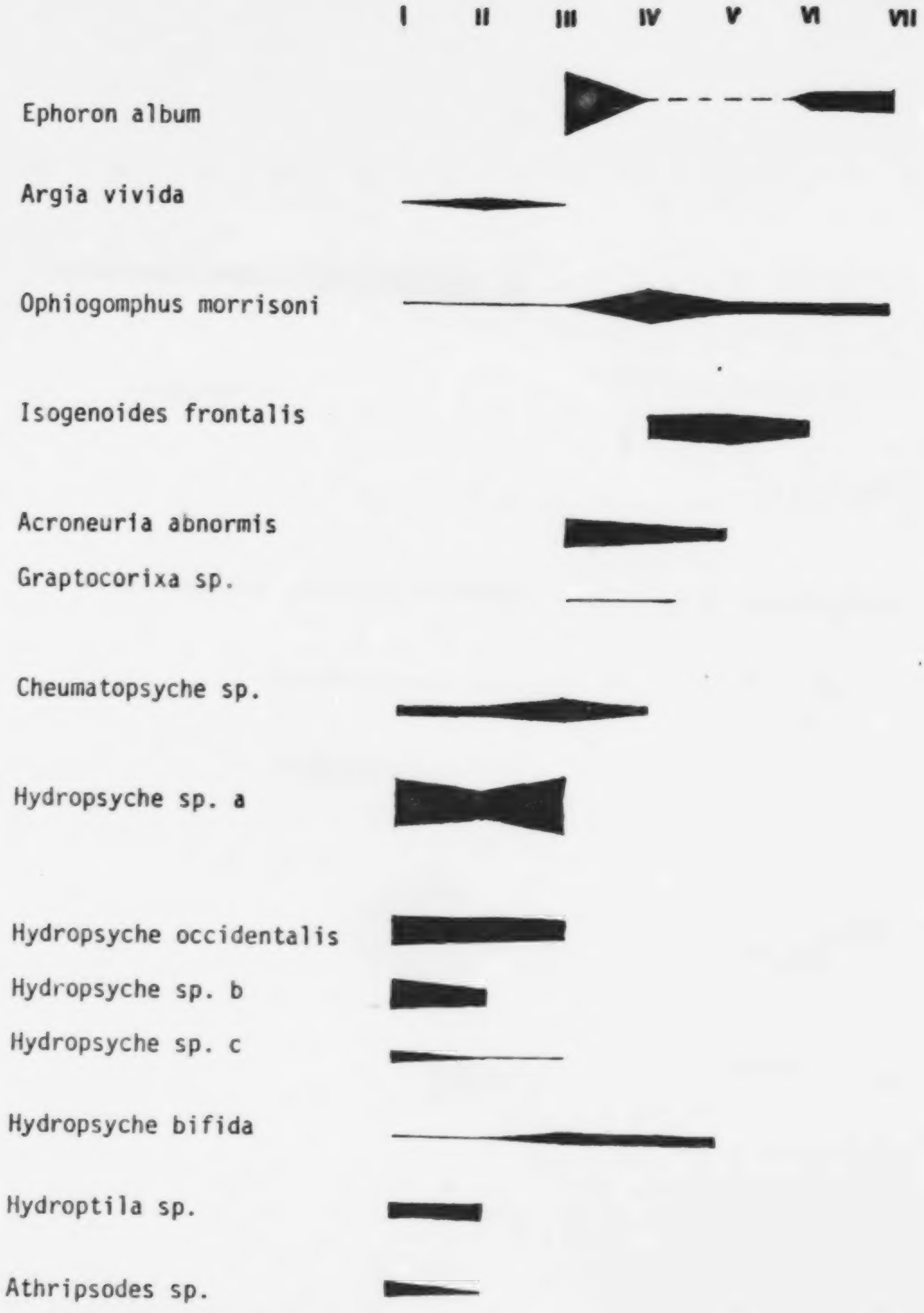


Figure D35 (cont.)

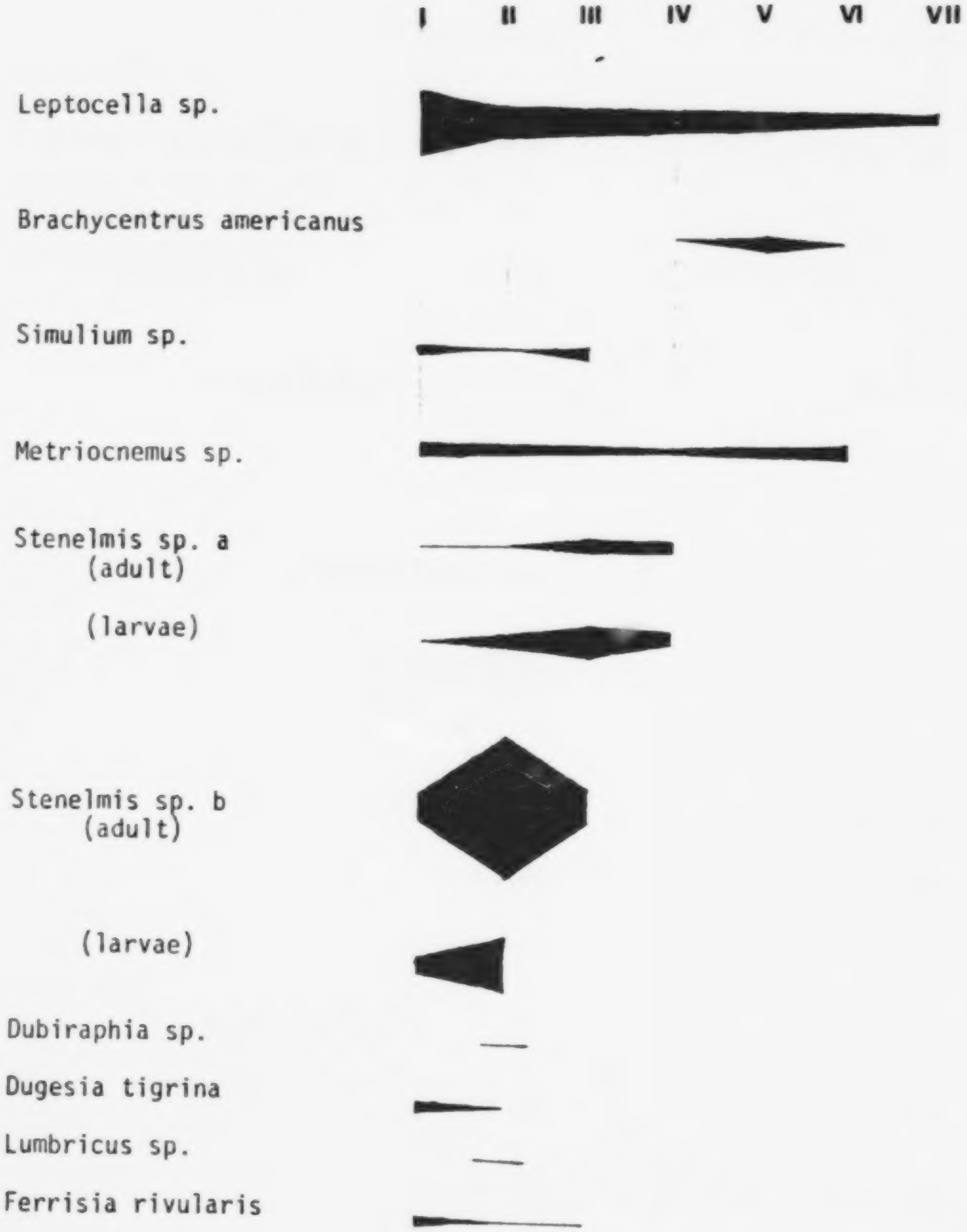
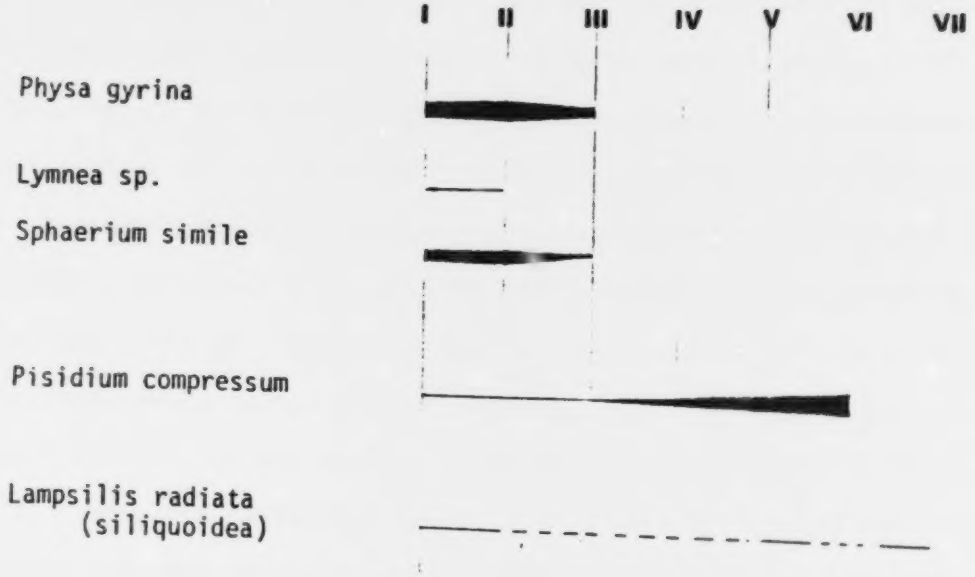


Figure D35 (cont.)



causes a marked decrease in the number of invertebrate species. Most organisms live best in a situation of thermal flux which synchronizes the life cycle and stimulates growth of insect instars. This information is supported by work on the mayflies by Ide (1935) and more recently by Trottier (1971) on the effects of temperature on the life-cycle of dragonflies.

Ward (1974) found that the South Platte River, in Colorado, was typical in its responses to hypolimnion srain from the Cheesman Dam. Benthic algae increased in the cold water section through a combination of decreased turbidity, increased nutrients, increased flow constancy, and decreased bank and bed erosion. Filamentous chlorophytes were especially enhanced. Although densities of some invertebrates may increase below a reservoir, diversity is markedly decreased and increases slowly downstream. Ward also predicted that those species able to survive and mate under low temperature condition, and adjusted to depend on photoperiod and endogenous rhythms to avoid winter emergence, are those species most likely to be dominant in this area. In addition, Ward suggests that these are unstable communities within which a relatively minor biotic or abiotic change would produce great changes in community structure.

Lemkuhl (1972), in studies of the Saskatchewan River, has found that diapause eggs, which require temperature fluctuations to hatch, will hot hatch in areas influenced by hypolimnial release. Fifteen species of mayflies were found above the reservoir, and none in the thermally altered area below the hypolimnial release. Due to constant temperature, four criteria were not met: 1.) the necessity of freezing temperatures to break egg diapause; 2.) a rapid fluctuation from freezing to higher temperatures to induce hatching in some species; 3.) the requirement of a minimum termperature over a given period of time to stimulate nymph maturation; and 4.) a certain number of degree days at high temperatures for emergence to take place. The inference is made that non-mayfly aquatic insects, which often have similar requirements, are eliminated from these areas for the same reasons. Spence and Hynes (1971) have also found that lowered temperatures cause the increase in growth and abundance of periphyton (by reduing the number of grazers), which leads to a radical alteration of the substrate. This eliminates many substrate specific organisms and increases the number of available microhabitats for those species which would be less abundant under normal conditions. Spence and Hynes argue that the effects of a hypolimnial release changes the benthos in the same way as mild organic pollution.

Pearson, Kramer, and Franklin (1968) and Ward (1974) found that with increasing distance from the dam, atmospheric conditions and tributary waters combine to return the river to its pre-impoundment state and the numbers of invertebrate species increase. Depending on the discharge rate, the depth of the hypolimnion, and the hydraulic geometry of the river, the hypolimnial effects can extend to a distance of 150 km. below the reservoir.

Radford and Hartland-Rowe (1971), from their work on the Kananaskis River in Alberta, found that areas affected by hypolimnial release show low diversity and densities of invertebrates. This situation continues into the uneffected portions of the river where densities and diversity of invertebrates increases, but is still substantially lower than in similar unimpounded rivers.

Hilsenhoff (1971), working on Mill Creek in Wisconsin, has found that preimpoundment surveys showed diverse fauna of Ephemeroptera, Trivhoptera, Diptera, and Coleoptera. After impoundment the community was almost completely eliminated and replaced with Simuliidae and Chironomidae. Increases in total phosphorus and nitrogen, as well as altered thermal regime, were the implied causes for the change in community structure.

Isom (1969) and Bates (1962), in separate investigations on influences of mainstream impoundments in the Tennessee Valley, have found a decline in mollusc diversity as a result of hypolimnial releases. Although the unionicean clams were greatly reduced, the Lampsilinae and other smaller clams persist and often make up the entire community in the area directly below a hypolimnial drain reservoir. Trotzky and Gregory (1974) found the same effects of hypolimnial discharge dams on woodland streams in Maine.

The Tongue River Reservoir dam has a hypolimnial discharge and the biological situations described above are distinctly exhibited on the Tongue River. In the area of the river affected by the hypolimnial discharge the insect fauna is diminished and the dominant forms are the molluscs *Physa gyrina* and *Sphaerium simile*, along with the riffle beetle *Stenelmis sp. b*. Based on the collection point data (Table D4), the cold water area is also an area of low turbidity and increased periphyton, as exemplified by the dense mats of *Cladophora*. Stolier (1963) observed similar relationships between a hypolimnial dam release and *Cladophora* on the Marias River in Montana. These dense mats of *Cladophora* apparently provide a tremendous increase in the availability of suitable habitats for the riffle beetles, as large numbers (up to 2250 individuals/m^2) have been found inhabiting the dense mats of filamentous algae. Open areas of small and medium cobble are, likewise, inhabited by large numbers of *Sphaerium* and *Physa* (400 individuals/m^2).

Elliott (1967) and Hynes (1970) have shown that there is a definite trend for adults of the Ephemeroptera, Plecoptera, and Trichoptera to fly upstream for the purposes of oviposition. Although this event has not been investigated on the Tongue River, it is a likely occurence. However, assuming that Lemkuhl's hypotheses for the temperature requirements of diapause eggs is correct, the eggs deposited in the cold water section of the river do not undergo sufficient temperature fluctuations to break diapause. Thus, the insect larvae and nymphs, except in the few cases mentioned previously, do not occur in the cold water section and the insect eggs in this area probably remain in diapause until their death. Where the original temperature regime is re-established (at III' and downstream) the increase of the insect species is quite pronounced.

Van der Schalie (1973) has determined the temperature tolerances of many pulmonate snails, in particular Physa gyrina. The animals fail to feed and grow in areas where the mean water temperature is less than 4° C. In addition, although growth is faster at temperatures above 24° C., this advantage is offset by greater survival and reproductive abilities at lower temperatures. Although growth is possible at temperatures above 30° C., the organism will not reproduce. Thus, the physid snails seem to thrive best in waters where cool temperatures exist in the winter. These river conditions are reproduced in the area of the Tongue River influenced by the hypolimnial discharge. Because the higher summer temperatures of the middle river are not conducive to molluscan growth and reproduction and these greater temperature fluctuations are conducive to proper insect development as well, Physa and Sphaerium are diminished or eliminated and the dominant invertebrates are the hydropsychids and Strophopteryx fasciata. In addition, the algal cover of Cladophora is reduced (through increased grazing and chemical changes) and Nostoc is present.

Even though diversity has increased, due to a return to warm water conditions of thermal flux and increased suspended and organic matter in the water from tributary and irrigation flow, the communtiy may still be considered impoverished. Compared to invertebrate communities in a similar unimpounded river, the Middle and Lower Yellowstone (Newell, 1975), the number of species of invertebrates at any station on the Tongue River is considerably lower. Although the environments are similar, the influence of the hypolimnion discharge is dominant.

Finally, as the river nears its junction with the Yellowstone River, a third community is present. Increased turbidity causes the amount of available light to be reduced, and the abrasive action of suspended particles fouls many insect gills or causes alteration of the substrate to other than optimum conditions (Hynes, 1970). Thus, in the area of the lower river, where turbidity is high, the benthic fauna is dominated by Cheumatopsyche, which can take advantage of the suspended matter in its feeding habits. The dominant algal form in this area is Nostoc.

The Effect of Flow Reduction:

In order to reduce pressure on the Tongue River dam during a six week period, the control gates were left open during the greater part of the spring and summer of 1975 to drain the reservoir as much as possible. This continual release of water from the reservoir did not allow complete formation of a hypolimnion layer. Water released during this period was observed to have temperatures only 1° or 2° C. cooler than at the mouth of the river at Miles City (Figure D36). The release of water at these elevated temperatures eliminated the cold water environment associated with the stretch of river below the dam.

The alteration of community structures can be seen in the dendrogram (Figure D33) and kite-diagram (Figure D37). Warming of this section of the river has apparently made it habitable to most of the insect species which are commonly found in the upper warm water section. The dendrogram shows that site III has become more closely associated with sites I and II. No clear dominant can be discerned in the "cold" water area; however, the hydropsychids and Stenelmis sp. b are most abundant and the formerly dominant Physa and Sphaerium are considerably reduced.

There are two possible explanations for the new community composition in the area. If the ideas of Lemkuhl (1972) are accepted and one assumes that adults fly upstream to lay eggs, the change in thermal regime to that of greater temperature fluctuations has probably allowed the hatching of diapause eggs, and nymphal and larval development of many insects, which the formerly cooler waters would not have allowed. The presence of individuals (in some samples)

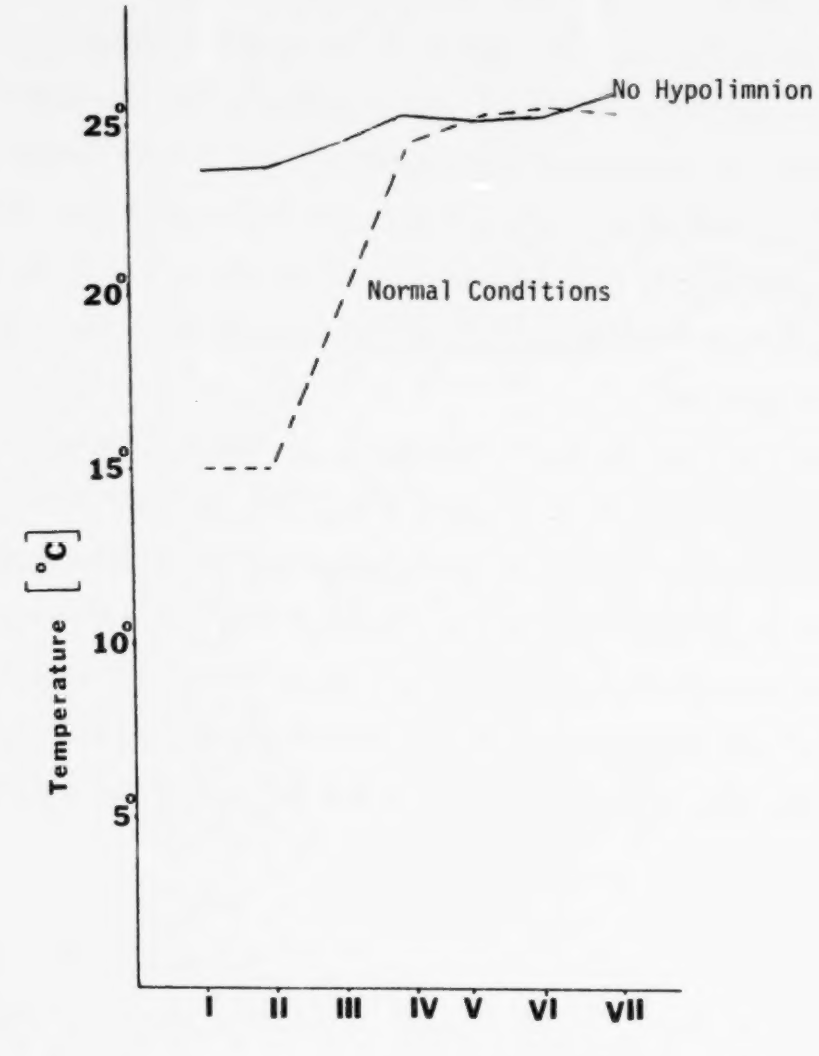


Figure D36. Summer Temperatures. Tongue River.

which are obviously not first or second instar (that is, some individuals close to emergence) precludes this idea as being the sole explanation.

Madsen, Bengtson, and Butz (1973) and Bishop and Hynes (1969) have shown the evidence of positive rheotaxis in aquatic insects, through the upstream migration of virtually all larval and nymphal stages of all the major groups of aquatic insects. Upstream migration is quite pronounced in the Ephemeroptera (particularly *Baetis*), the Trichoptera, the Coleoptera, and Diptera. Thus, the presence of many aquatic insects in this community seems to be due to the hatching of diapause eggs, influenced by thermal changes in the section, and the upstream migration of larval and nymphal forms to an area which had been formerly uninhabitable, and acted as an apparent barrier to upstream migration.

The lower part of the river, as shown by dendrogram (Figure D33), is no longer divided into two distinct communities. The dominance and great abundance of the two mayflies, *Traverella albertana* and *Rhithrogena hageni*, from sample point IV downstream dampens the effect of changes in number or occurence of the rarer species of aquatic insects. It should be noted as well, that the lower part of the river is dominated almost exclusively by short-lived summer species of mayflies which do not occur in the fall and winter samples.

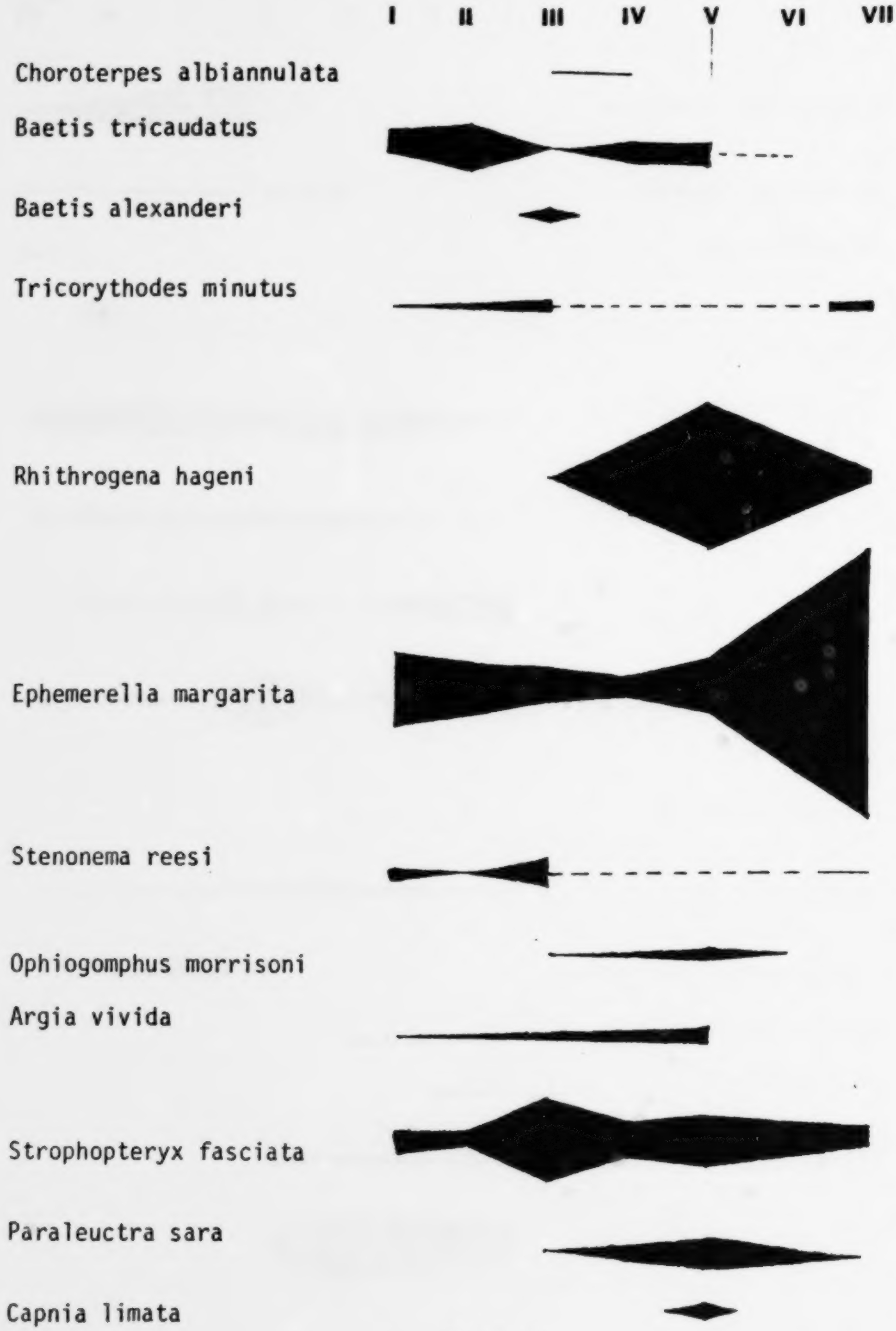


Figure D37. Distribution and Relative Abundance. Macroinvertebrates. After Massive Flow Reduction.

Figure D37 (cont.)

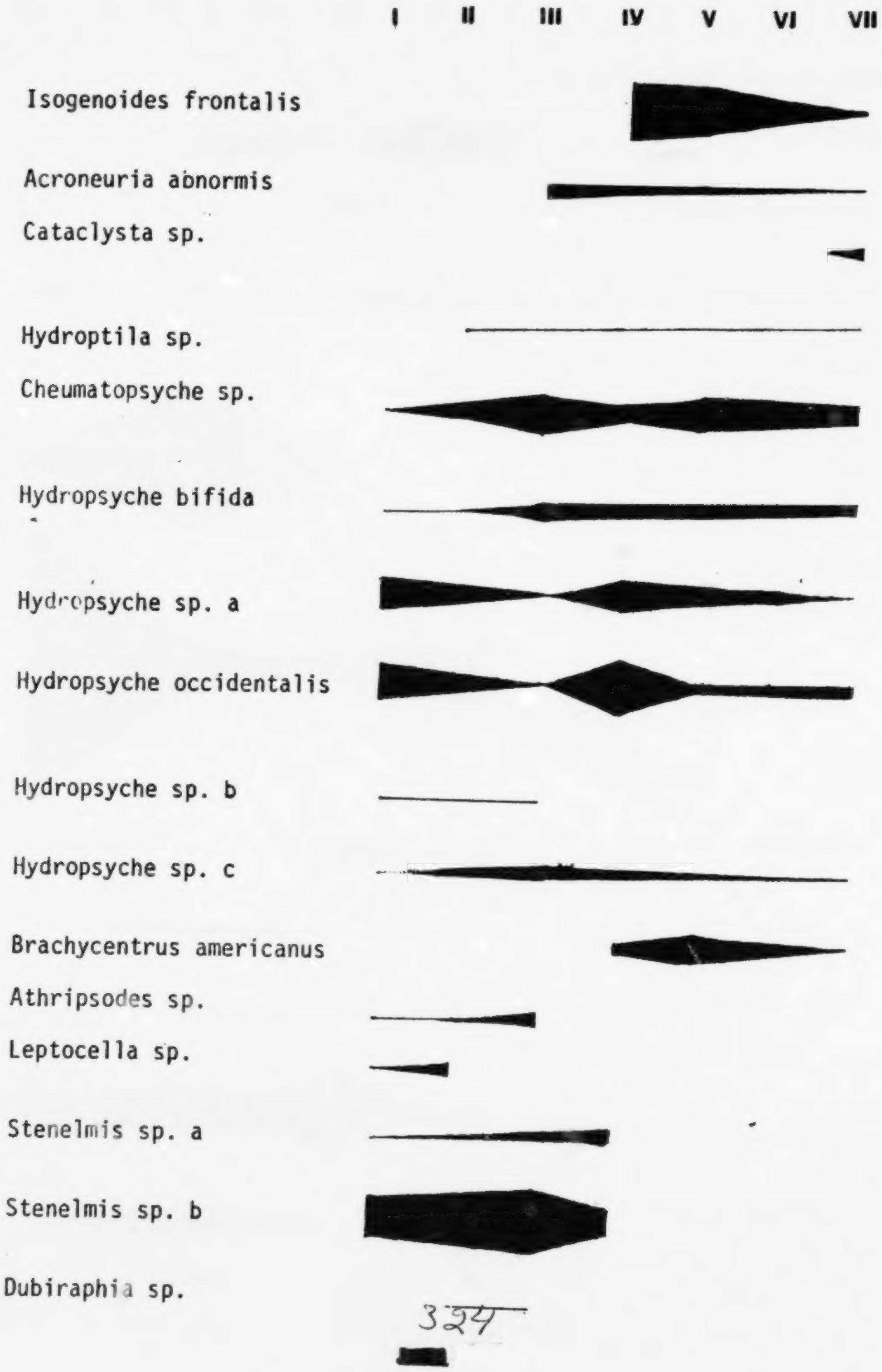
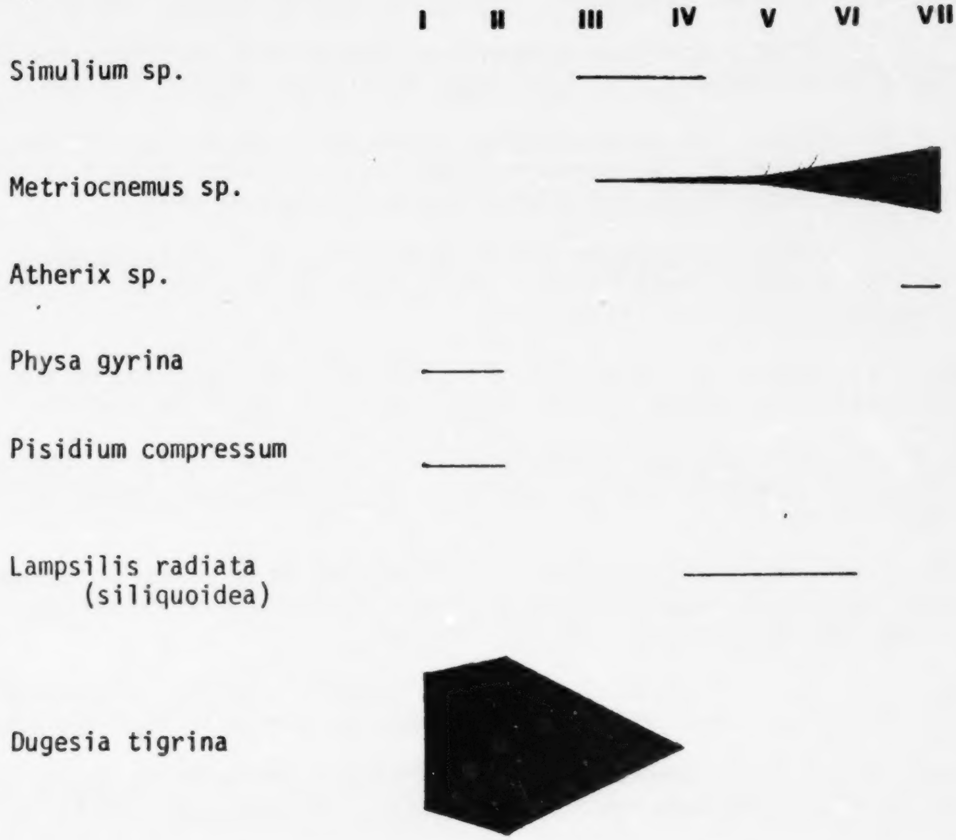


Figure D37 (cont.)



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APPENDIX E

HYDROLOGIC CONTOUR MAPS

SPAWNING CRITICAL AREA

1. Flow direction is from left to right.
2. For easier interpretation, depth contours are indicated by vertical typeface. Velocity contours are indicated by slanting typeface.
3. Hatchered areas on contour maps indicate isolated areas of reduced depth or velocity, depending on the type of map.
4. Dashed lines indicate edge of water, either at stream banks or on exposed bars.

Figure E-1: Substrate Map of the Ft. Keogh Spawning Section.

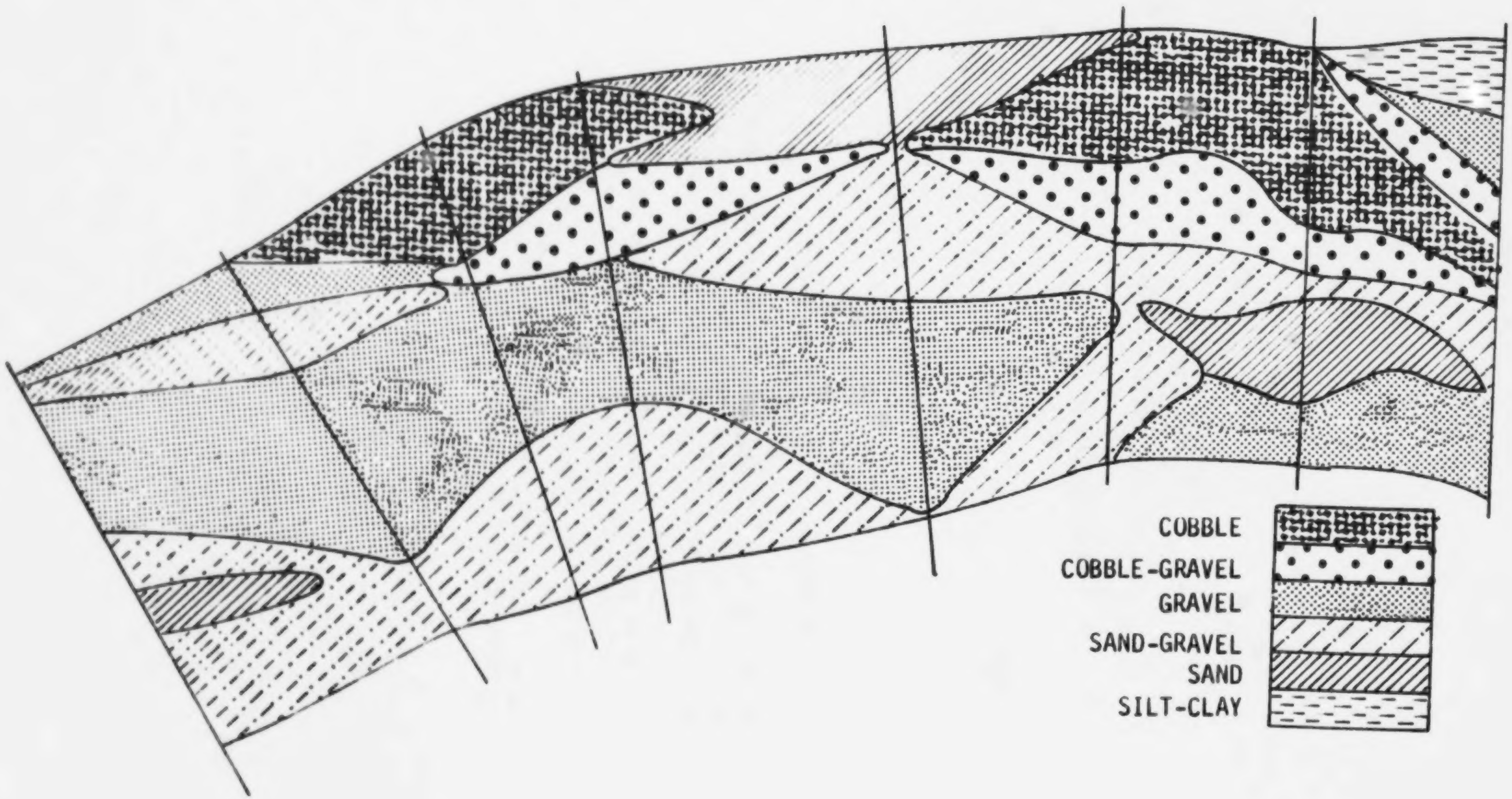


Figure E-2: Velocity Contour Map for the Ft. Keogh Spawning Section, with Velocities in cm./sec. Discharge: 11.0 cms.

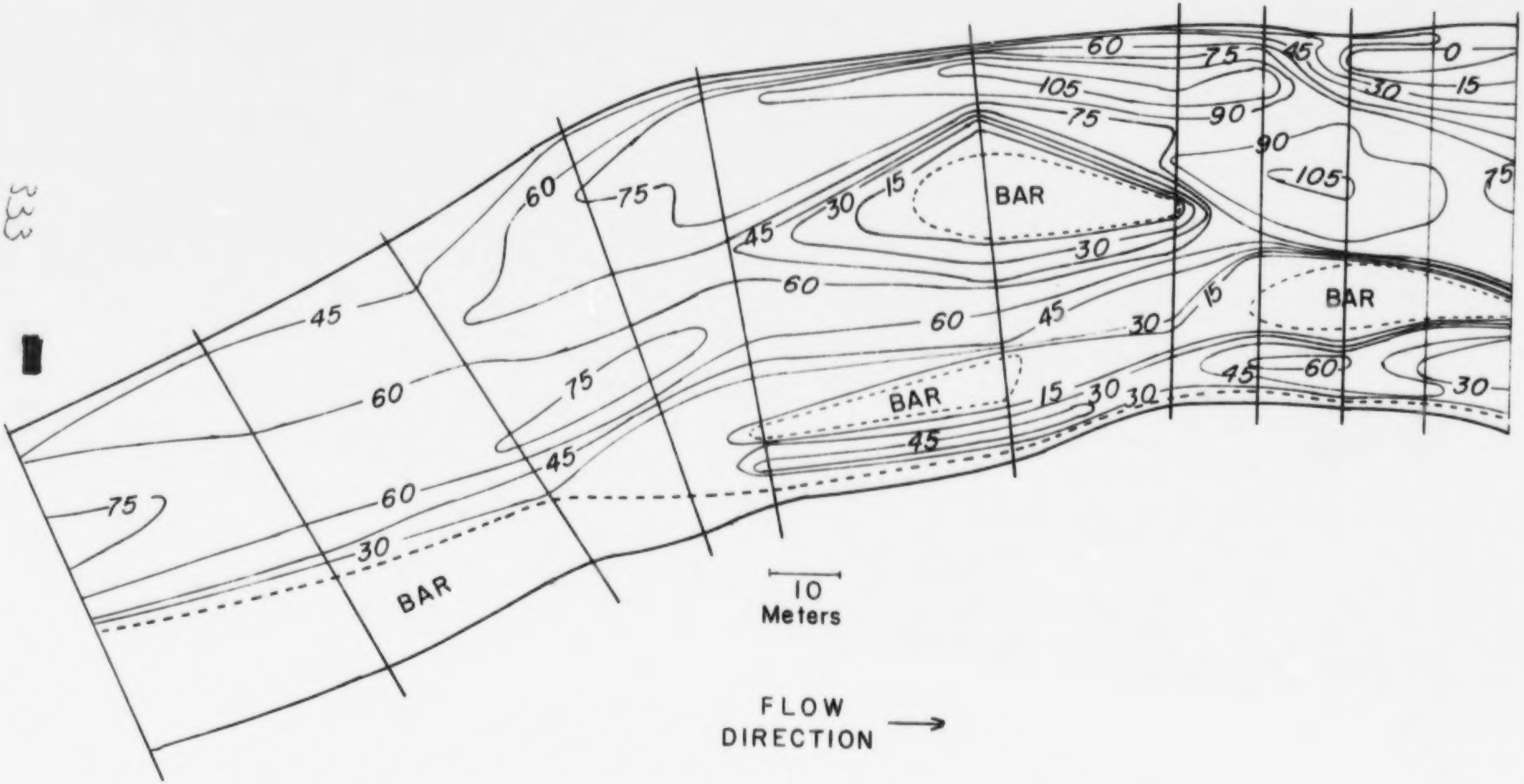


Figure E-3: Depth Contour Map for the Ft. Keogh Spawning Section, with Depths in cm. Discharge: 11.0 cms.

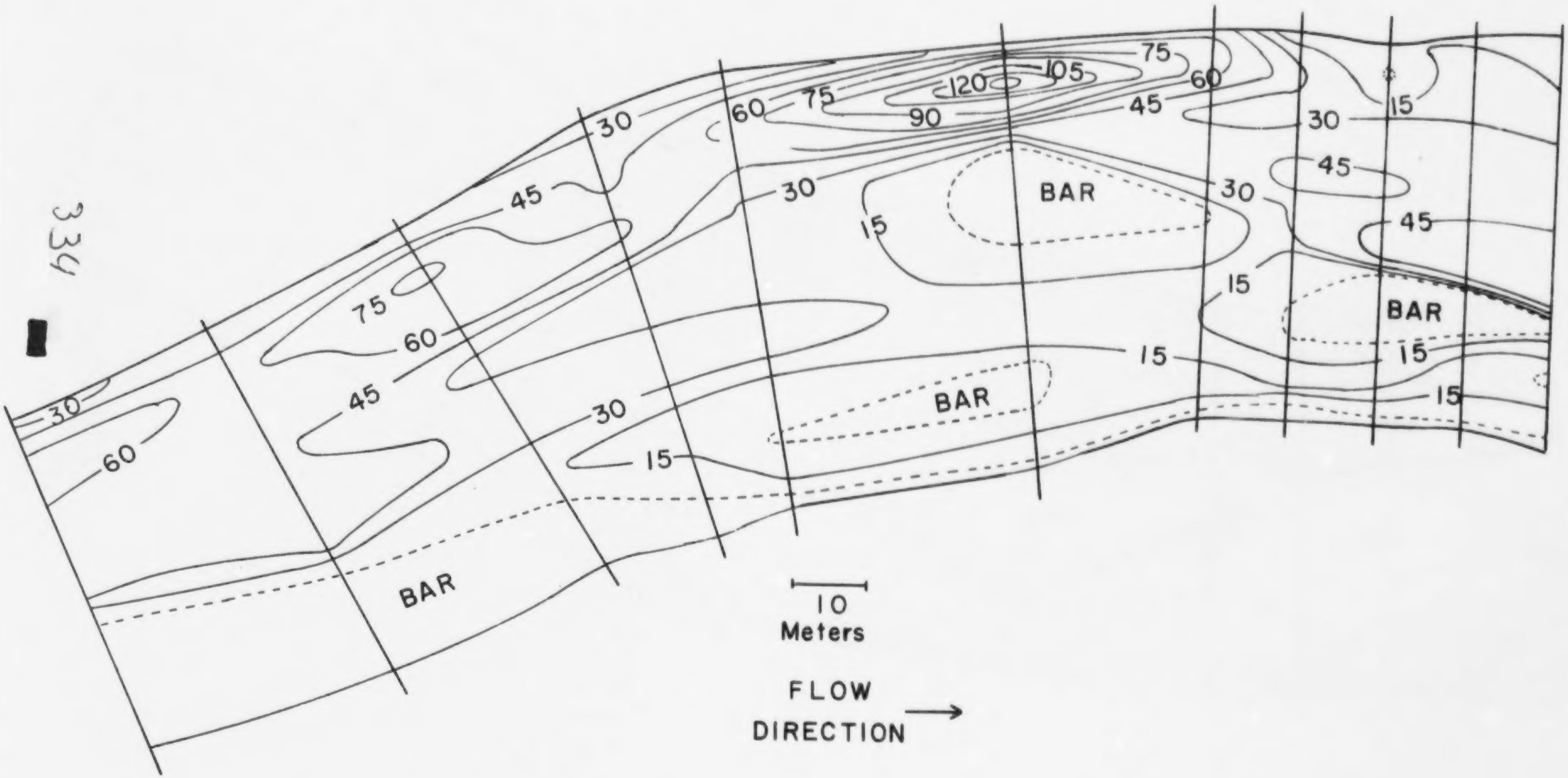


Figure E-4: Velocity Contour Map for the Ft. Keogh Spawning Section, with Velocities in cm./sec.
Discharge: 13.0 cms.

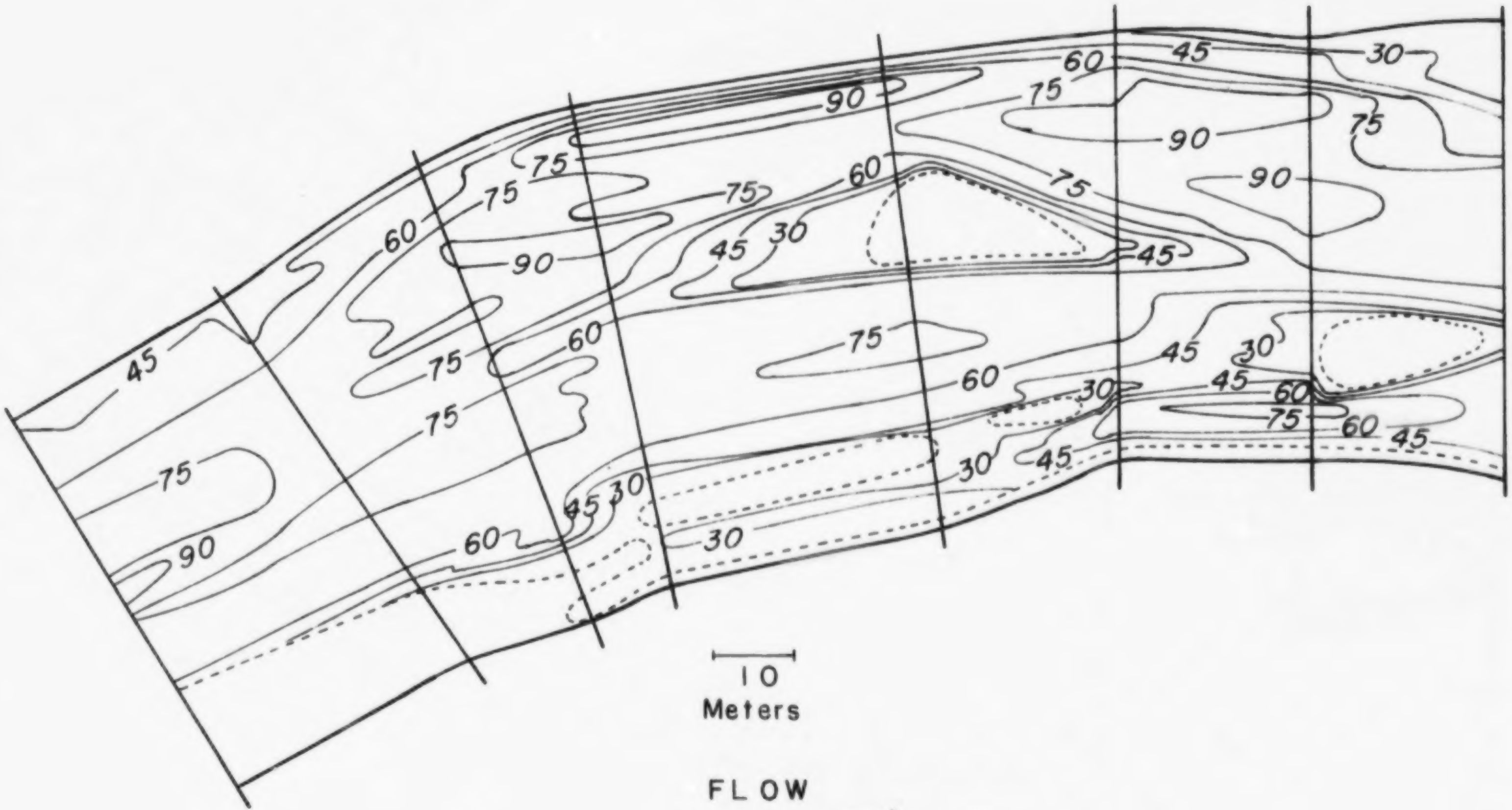


Figure E-5: Depth Contour Map for the Ft. Keogh Spawning Section, with Depths in cm.
Discharge: 13.0 cms.

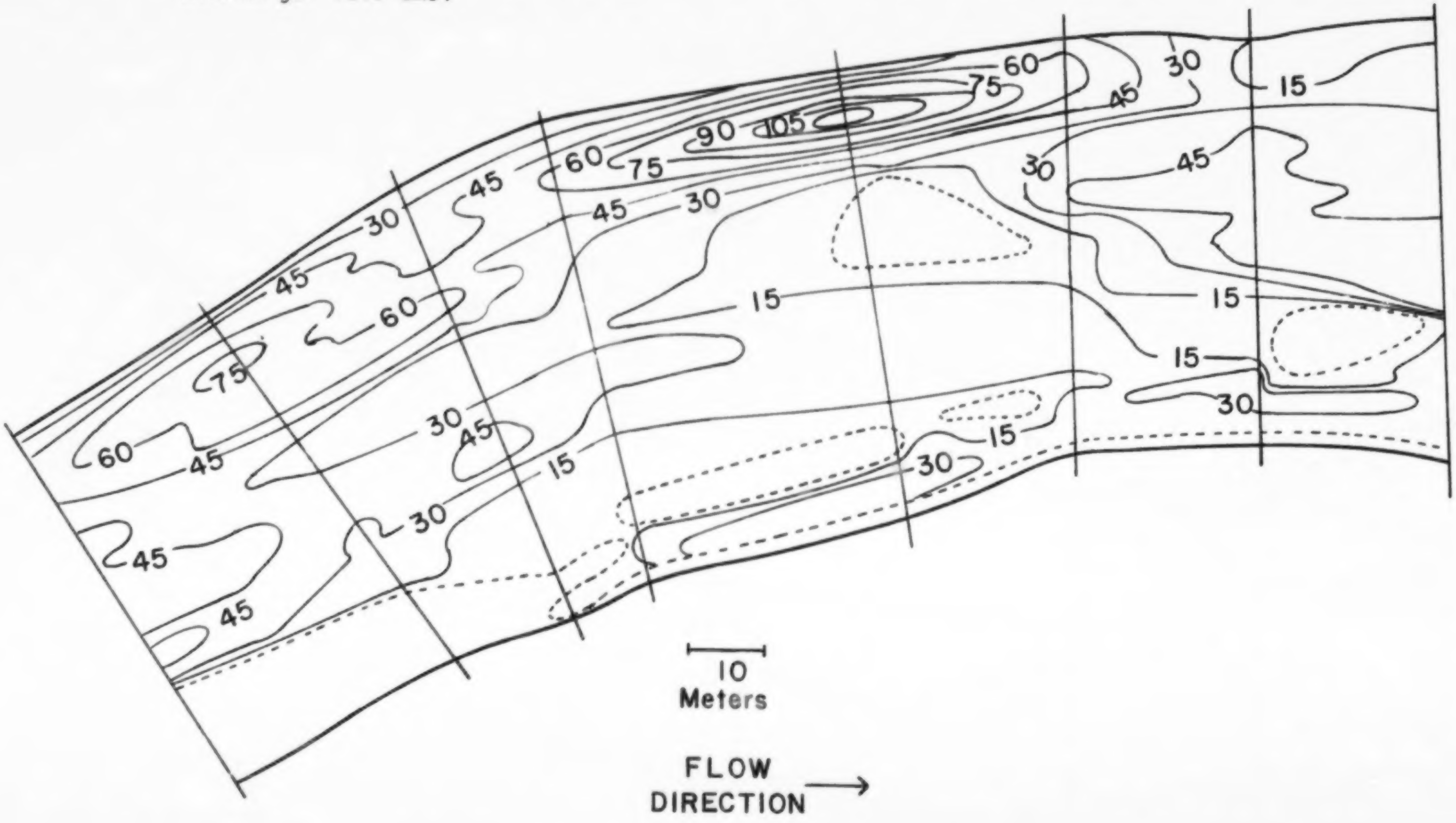


Figure E-6: Velocity Contour Map for the Ft. Keogh Spawning Section, with Velocities in cm./sec.
Discharge: 16.1 cms.

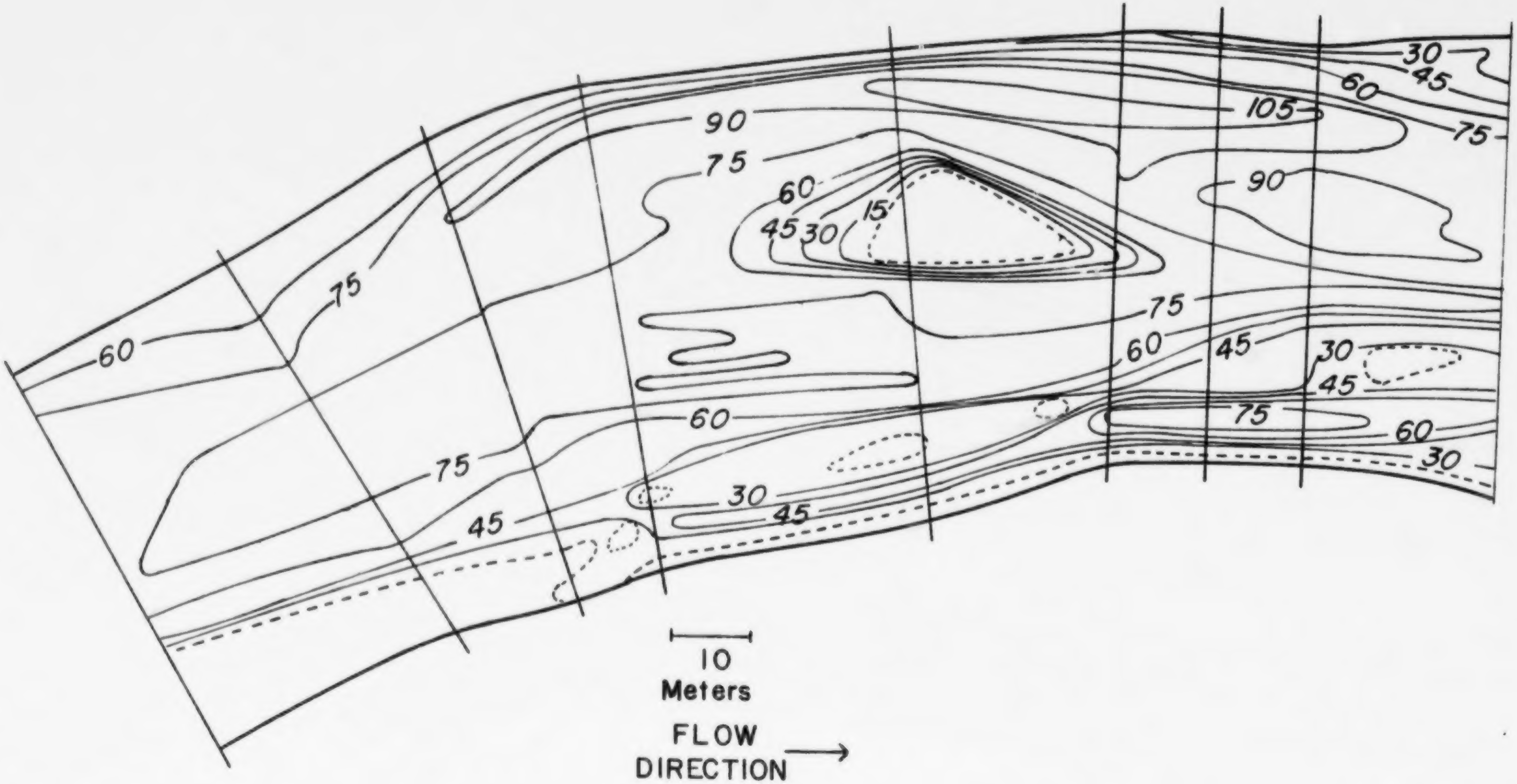


Figure E-7: Depth Contour Map for the Ft. Keogh Spawning Section, with Depths in cm.
Discharge: 16.1 cms.

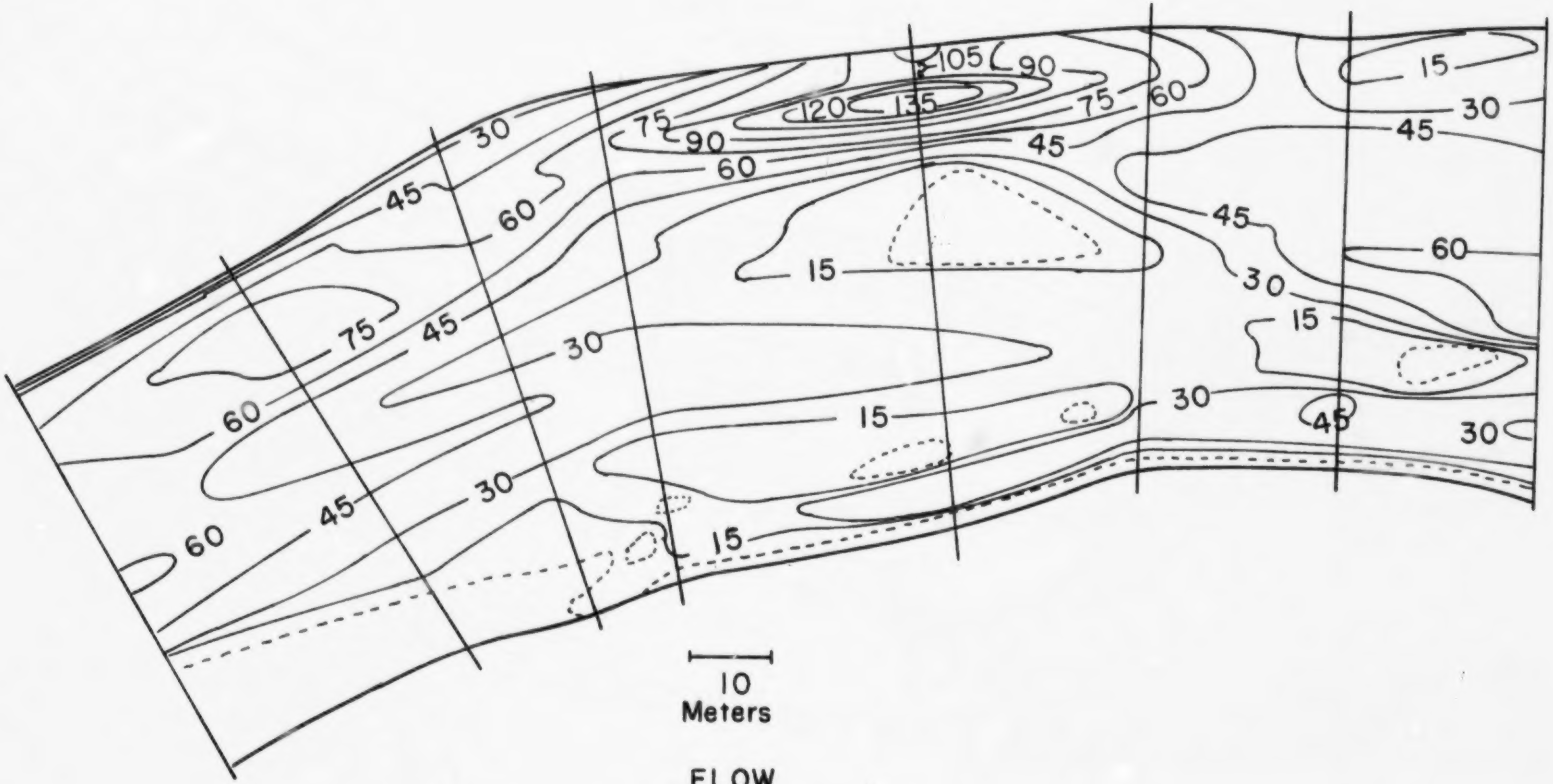


Figure E-8: Velocity Contour Map for the Ft. Keogh Spawning Section, with Velocities in cm./sec.
Discharge: 18.1 cms.

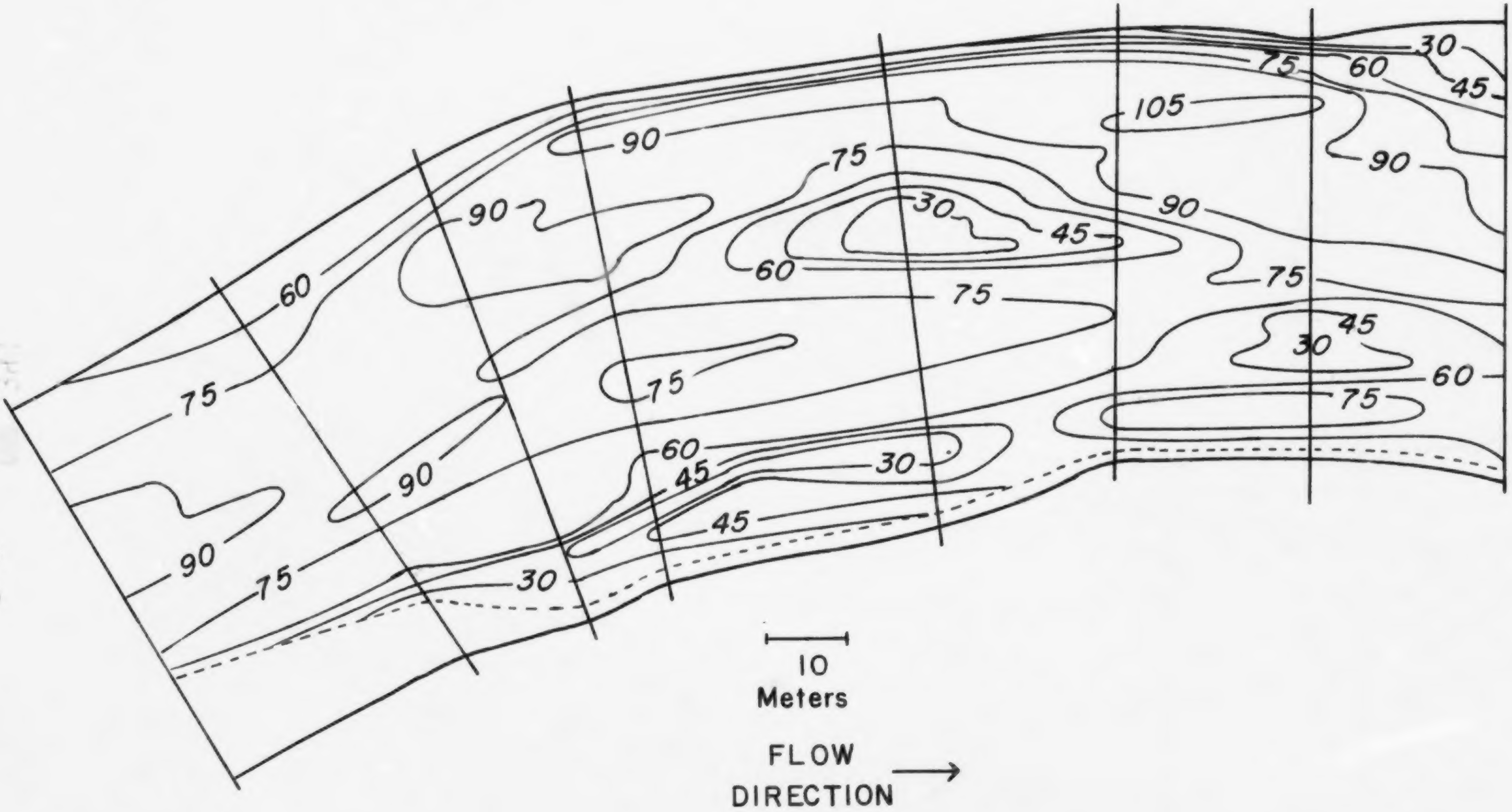


Figure E-9: Depth Contour Map for the Ft. Keogh Spawning Section, with Depths in cm. Discharge: 18.1 cms.

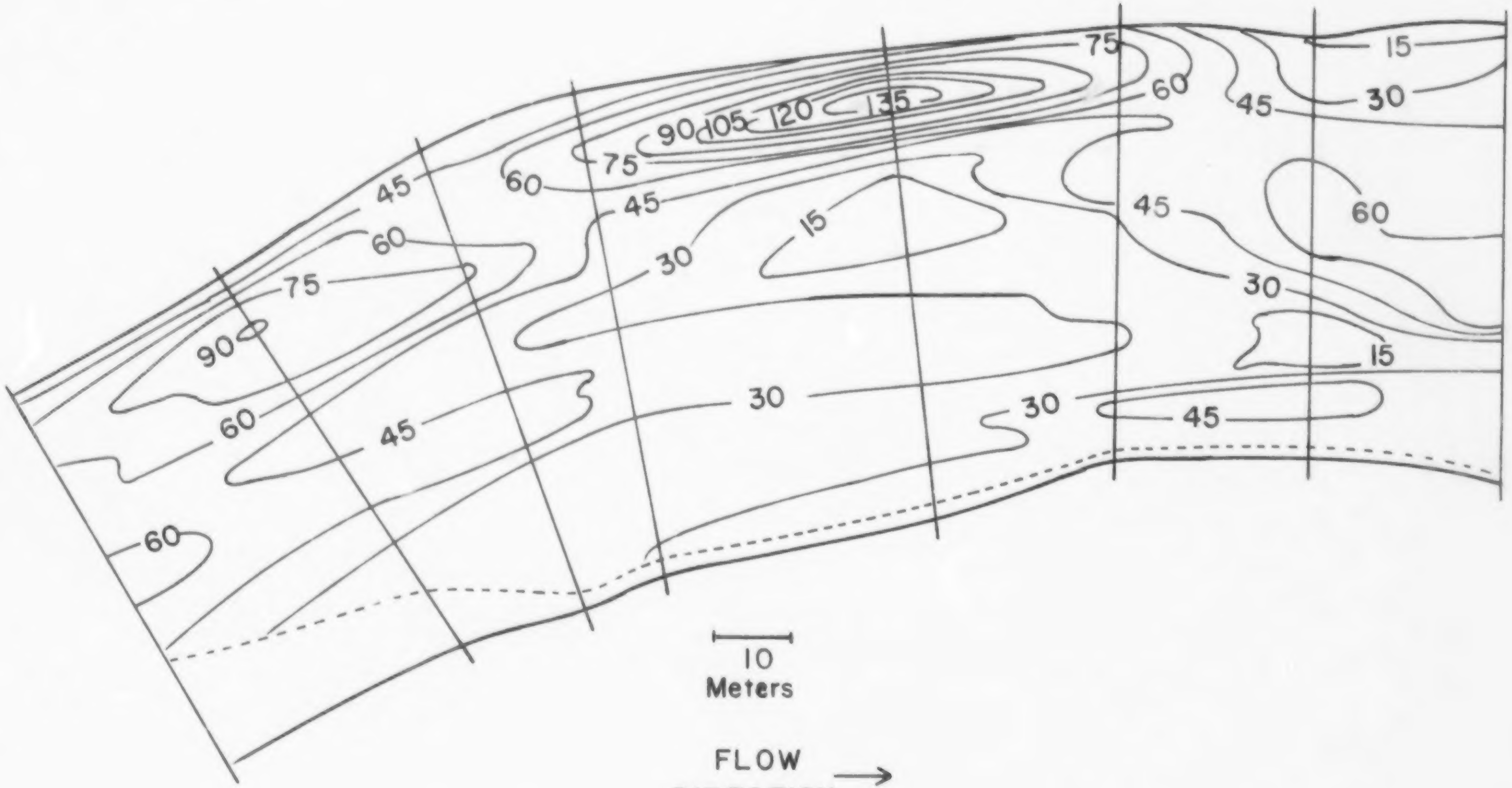


Figure E-10: Velocity Contour Map for the Ft. Keogh Spawning Section, with Velocities in cm./sec. Discharge: 20.2 cms.

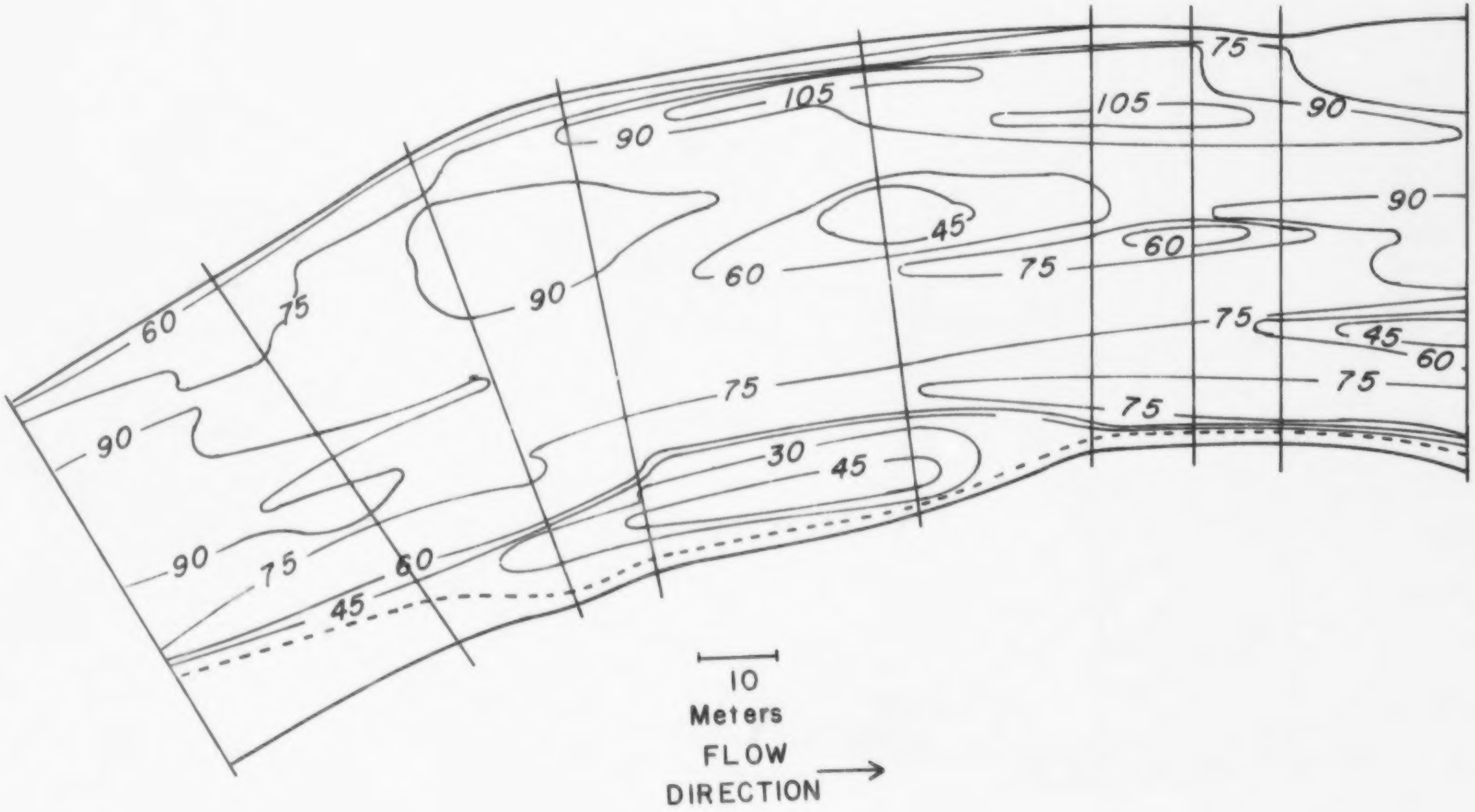


Figure E-11: Depth Contour Map for the Ft. Keogh Spawning Section, with Depths in cm. Discharge: 20.2 cms.

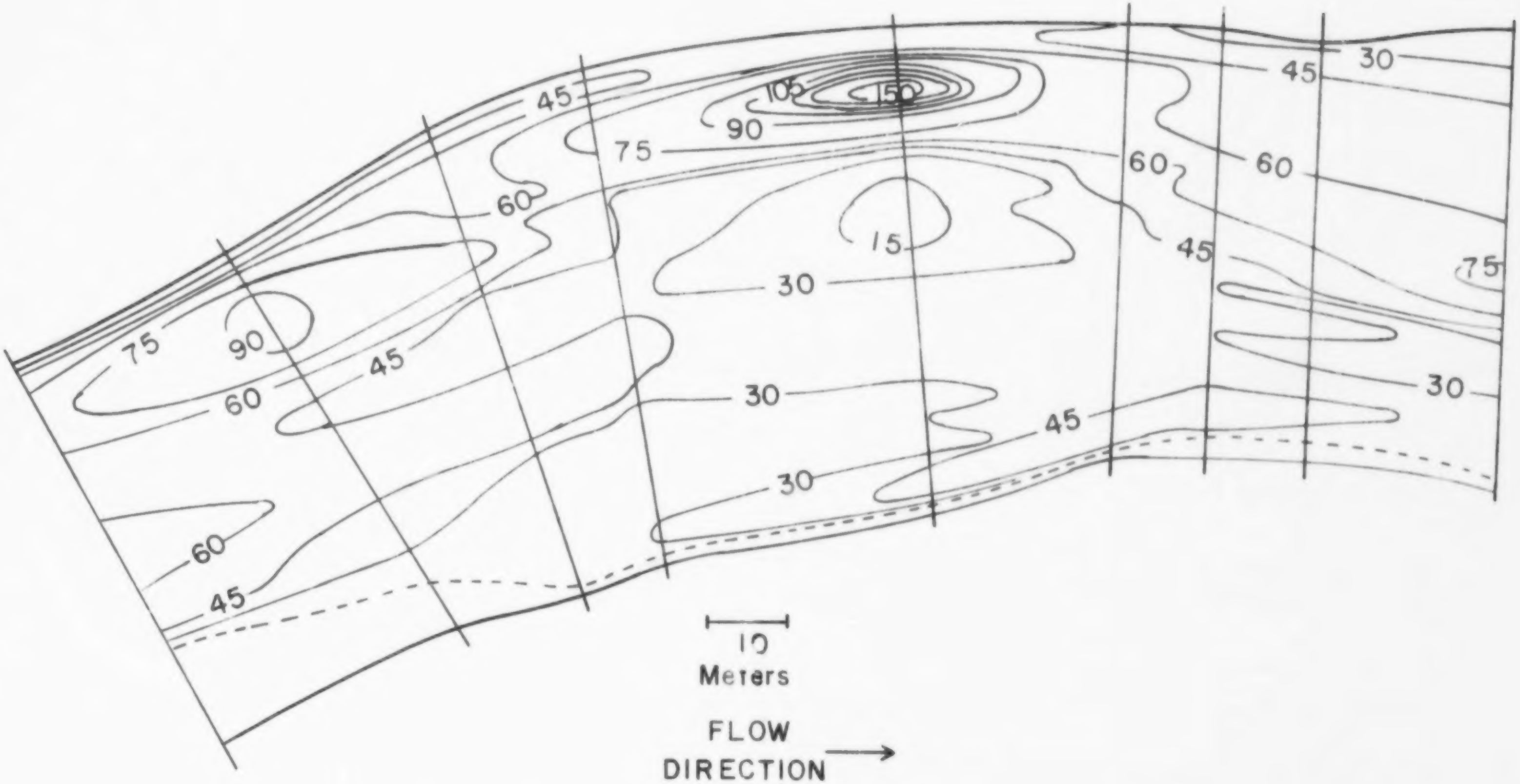


Figure E-12: Velocity Contour Map for the Ft. Keogh Spawning Section, with Velocities in cm./sec. Discharge: 22.5 cms.

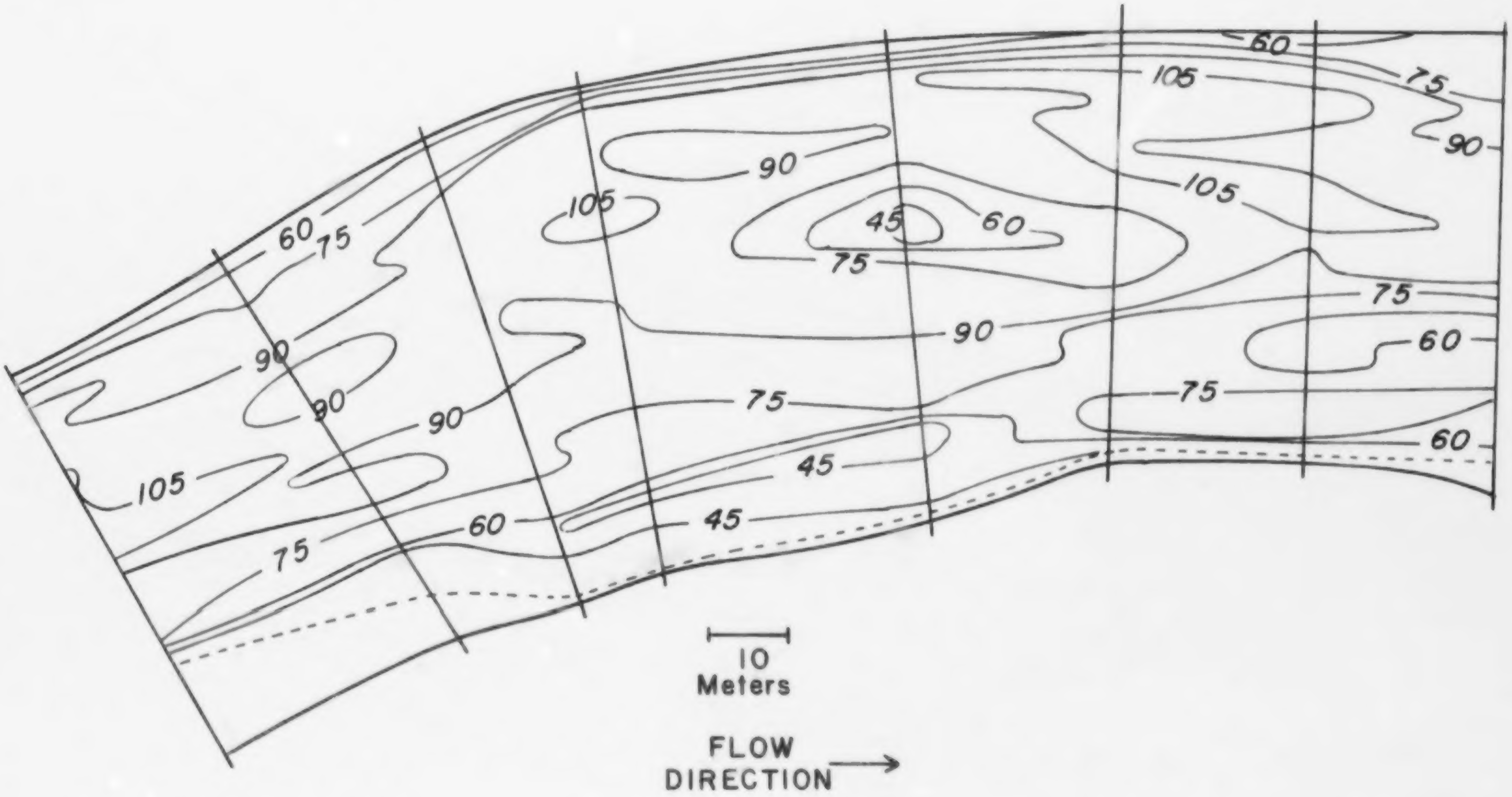
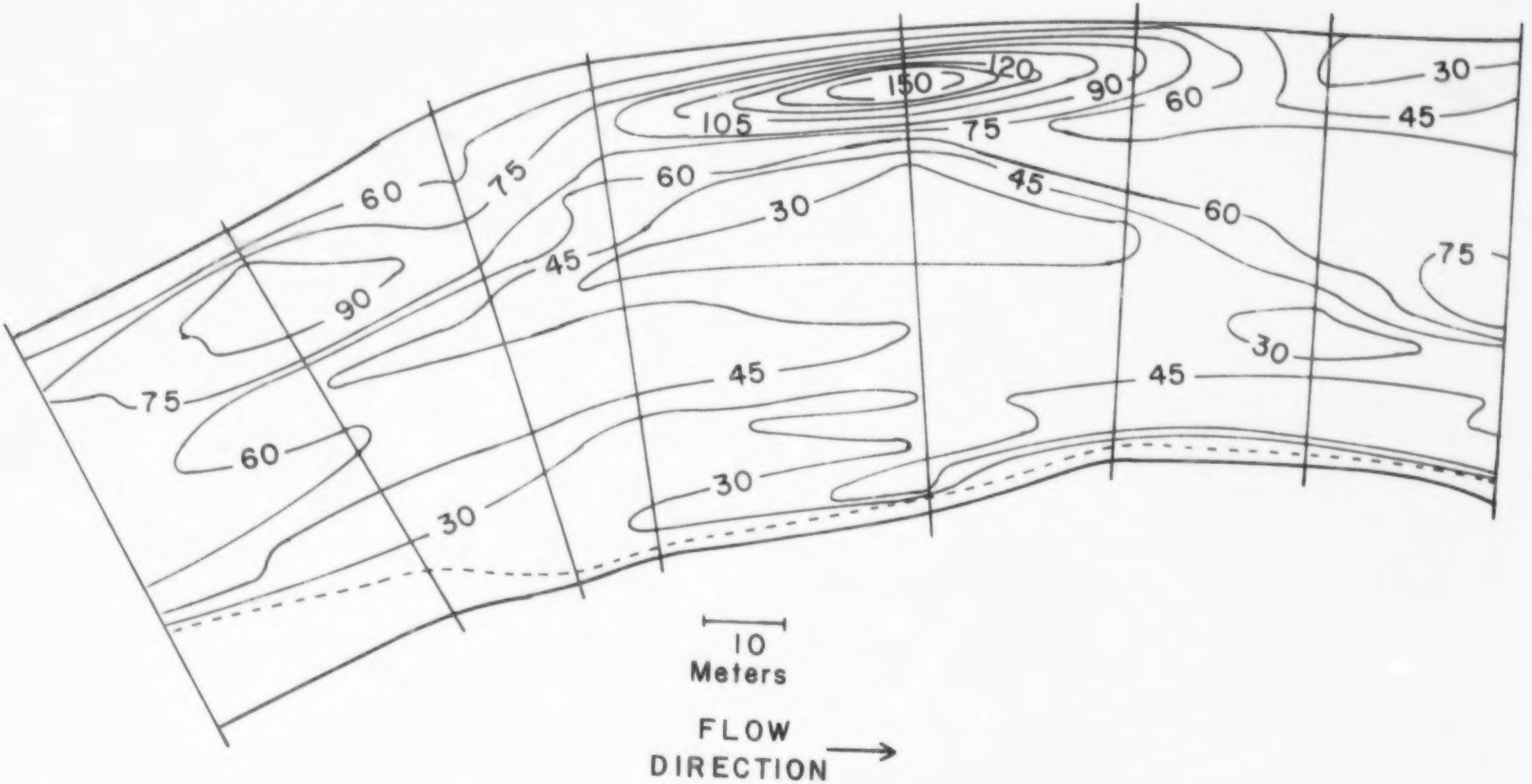


Figure E-13: Depth Contour Map for the Ft. Keogh Spawning Section, with Depths in cm.
Discharge: 22.5 cms.



E-14: Velocity Contour Map for the Ft. Keogh Spawning Section, with Velocities in cm./sec. Discharge: 25.5 cms.

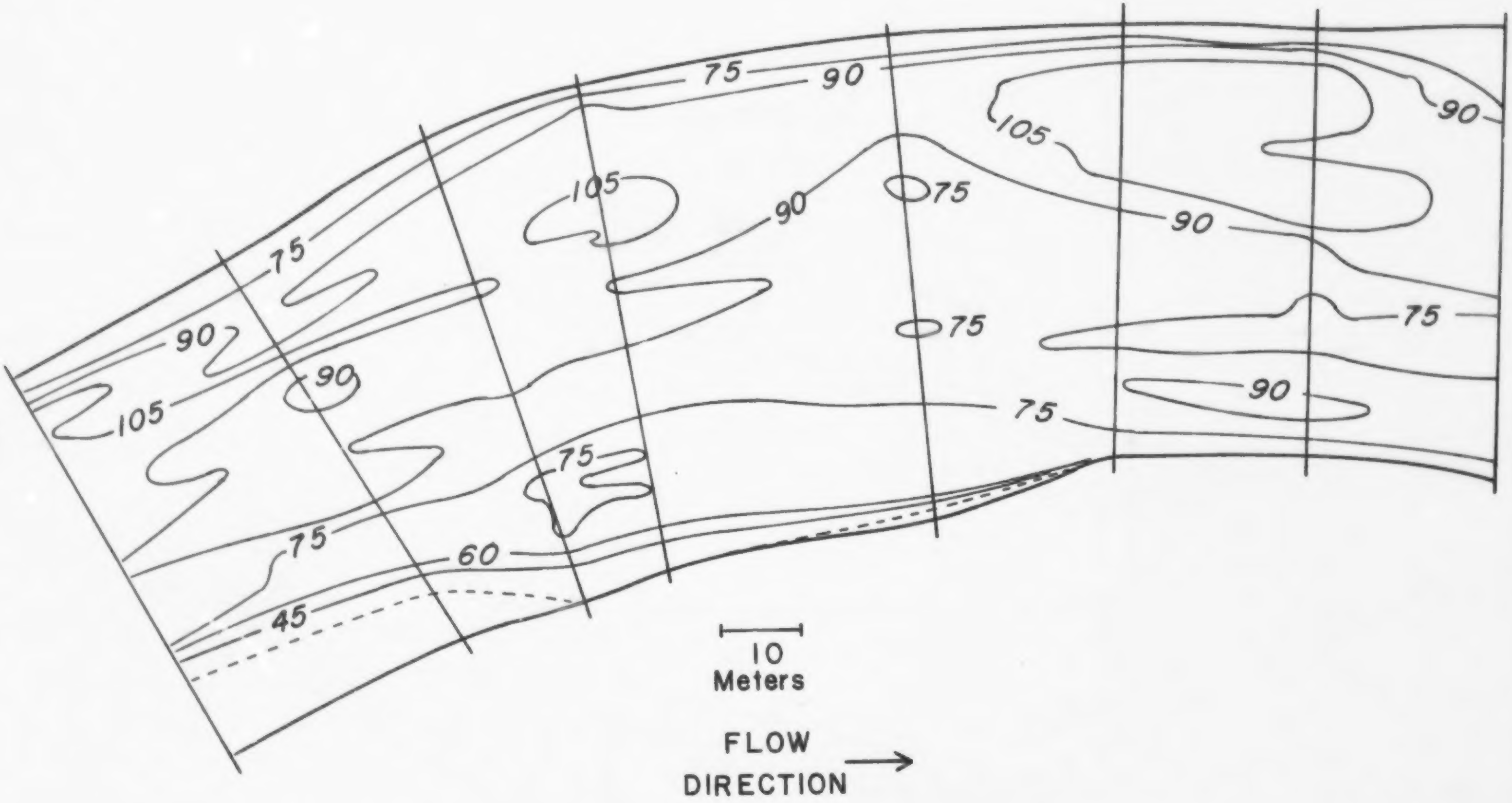


Figure E-15: Depth Contour Map for the Ft. Keogh Spawning Section, with Depths in cm.
Discharge: 25.5 cms.

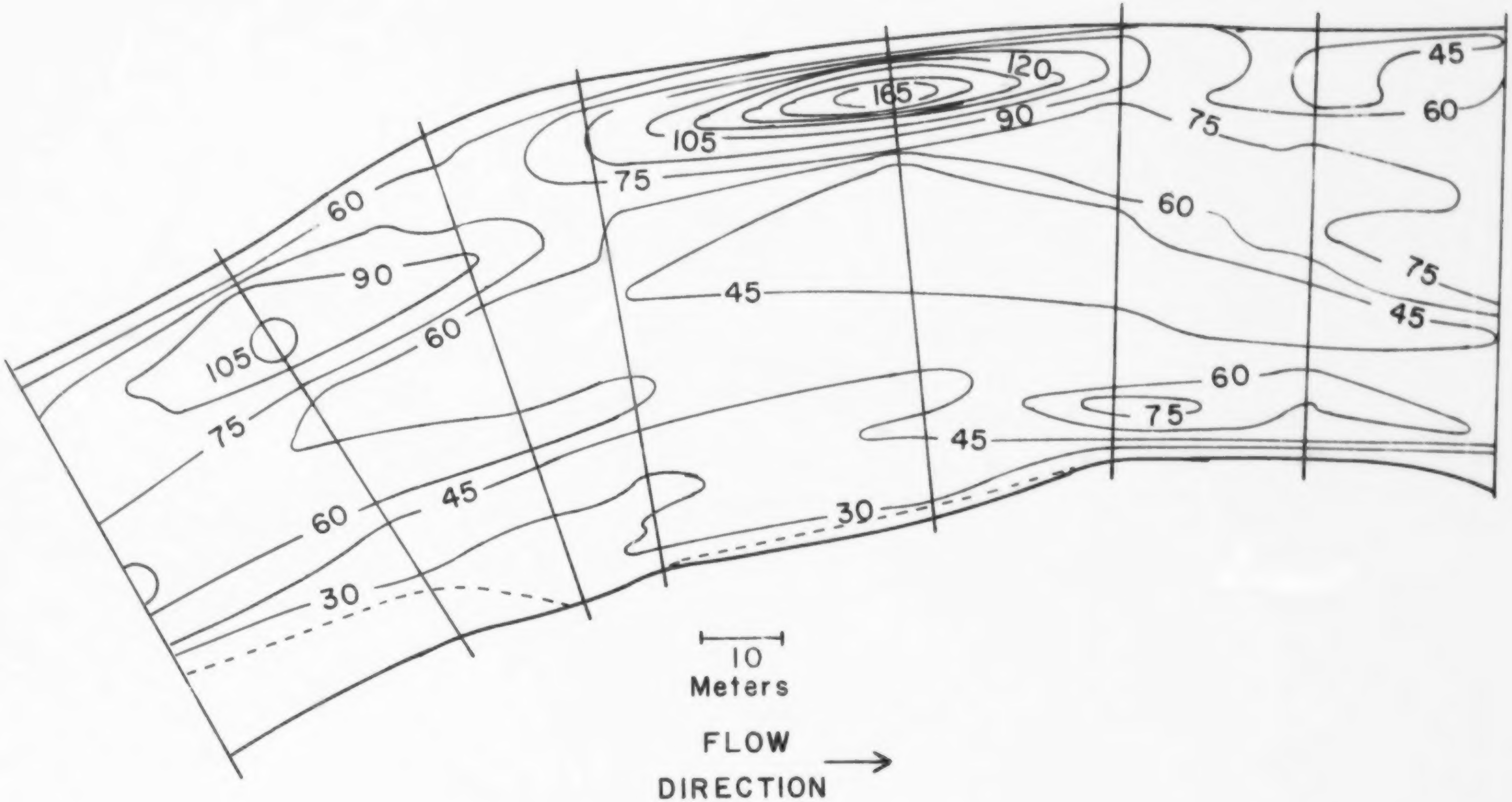


Figure E-16: Velocity Contour Map for the Ft. Keogh Spawning Section, with Velocities in cm./sec.
Discharge: 28.3 cms.

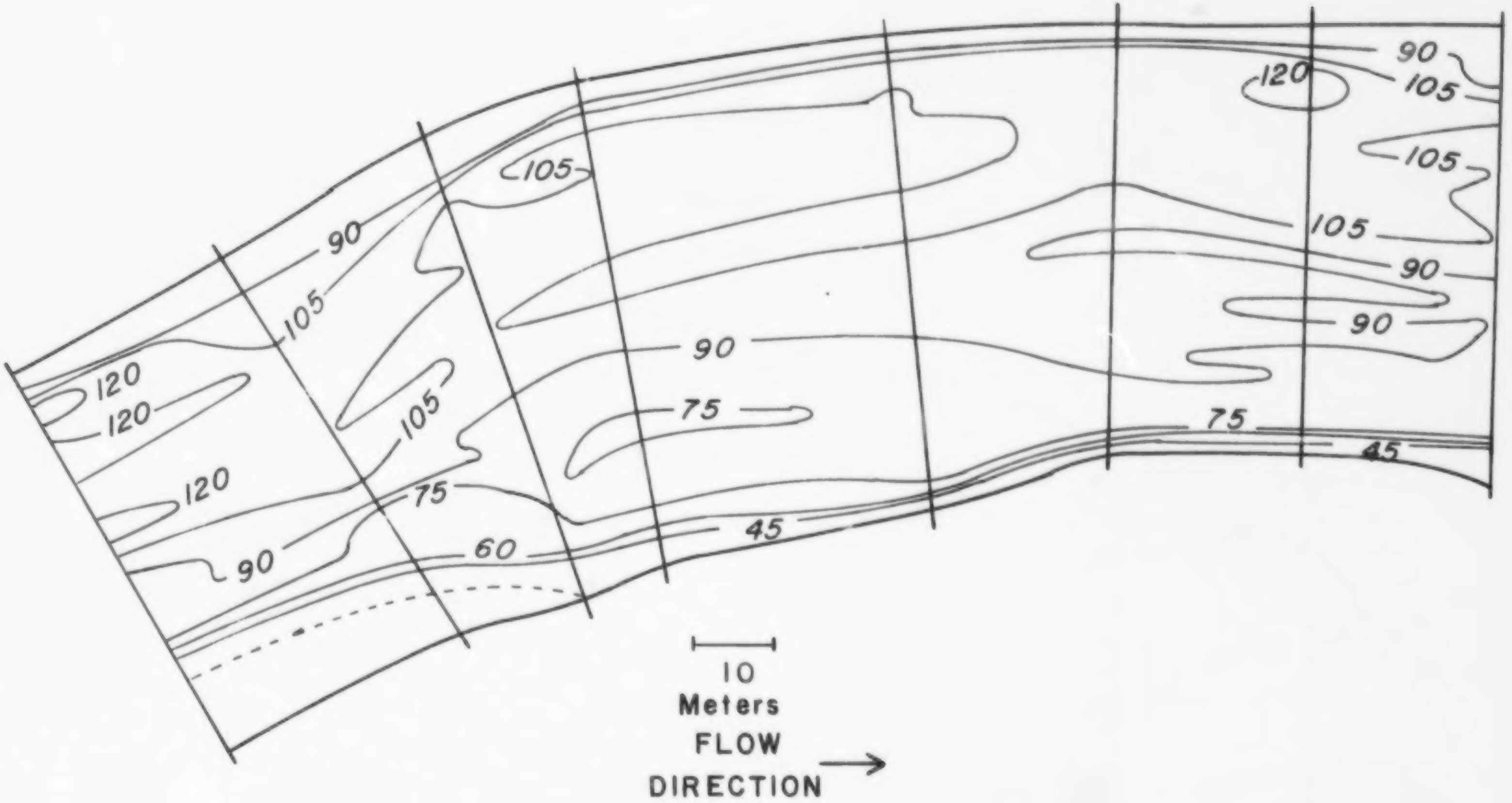
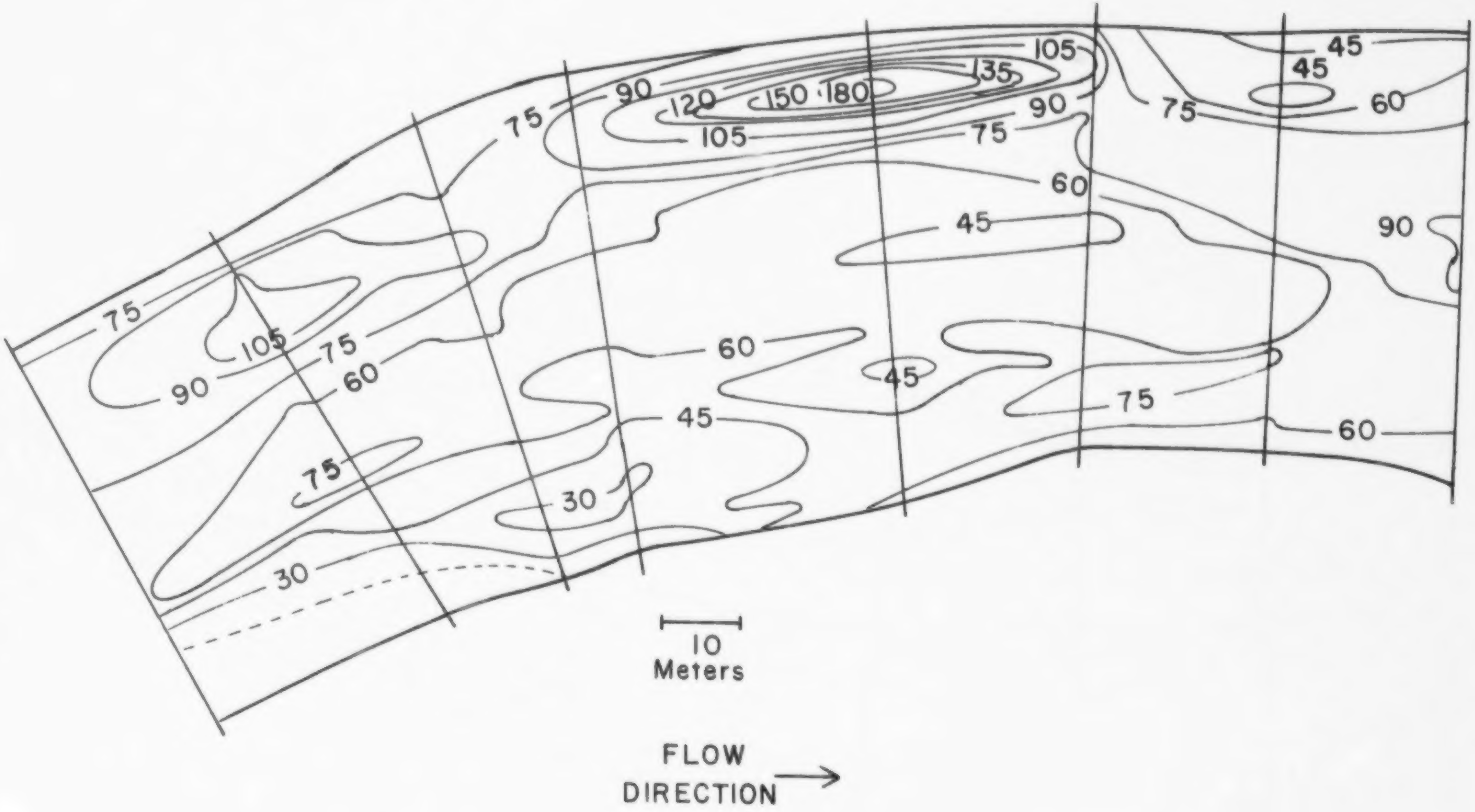


Figure E-17: Depth Contour Map for the Ft. Keogn Spawning Section, with Depths in cm.
Discharge: 28.3 cms.



APPENDIX F

COMPOSITE MAPS

SPAWNING CRITICAL AREA

1. Flow direction is from left to right.
2. These maps indicate areas meeting preferred conditions of depth, velocity, and substrate, for spawning shovelnose sturgeon.
3. For easier interpretation, depth contours are indicated by vertical typeface. Velocity contours are indicated by slanting typeface.
4. Cross-hatched areas on composite maps indicate areas which do not meet flow criteria for spawning shovelnose sturgeon. Only those stream areas without cross-hatching meet flow criteria.
5. Dashed lines indicate water's edge, either at stream banks or on exposed bars.

Figure F-1: Composite Map of the Ft. Keogh Spawning Section, Showing Areas Meeting Flow Criteria for Spawning Shovelnose Sturgeon.

Discharge: 11.0 cms.

Area Meeting Criteria: 290 m^2

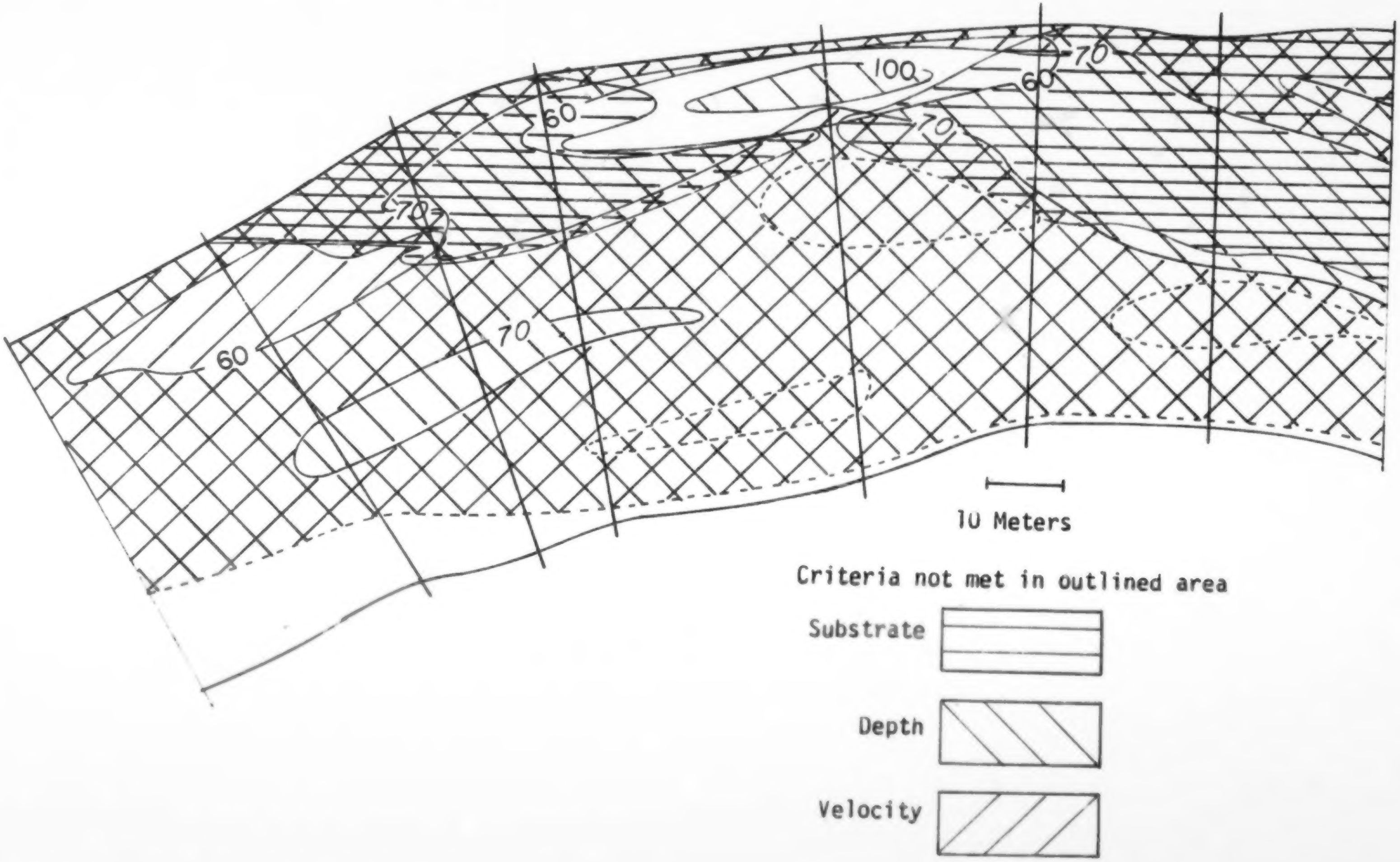
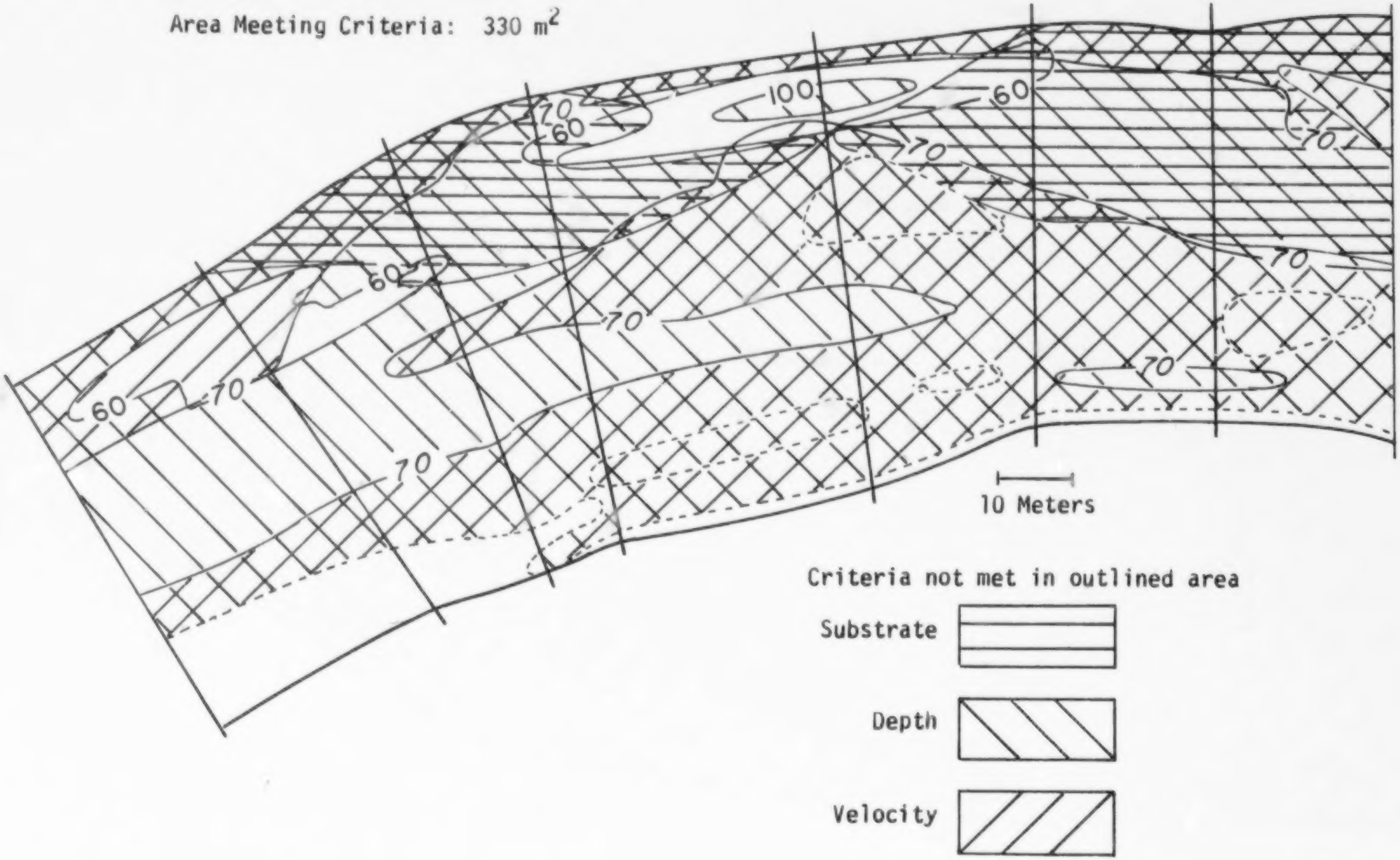


Figure F-2: Composite Map of the Ft. Keogh Spawning Section, Showing Areas Meeting Flow Criteria for Spawning Shovelnose Sturgeon.

Discharge: 13.0 cms.

Area Meeting Criteria: 330 m^2



[redacted]

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Figure F-3: Composite Map of the Ft. Keogh Spawning Section, Showing Areas Meeting Flow Criteria for Spawning Shovelnose Sturgeon.

Discharge: 16.1 cms.

Area Meeting Criteria: 570 m^2

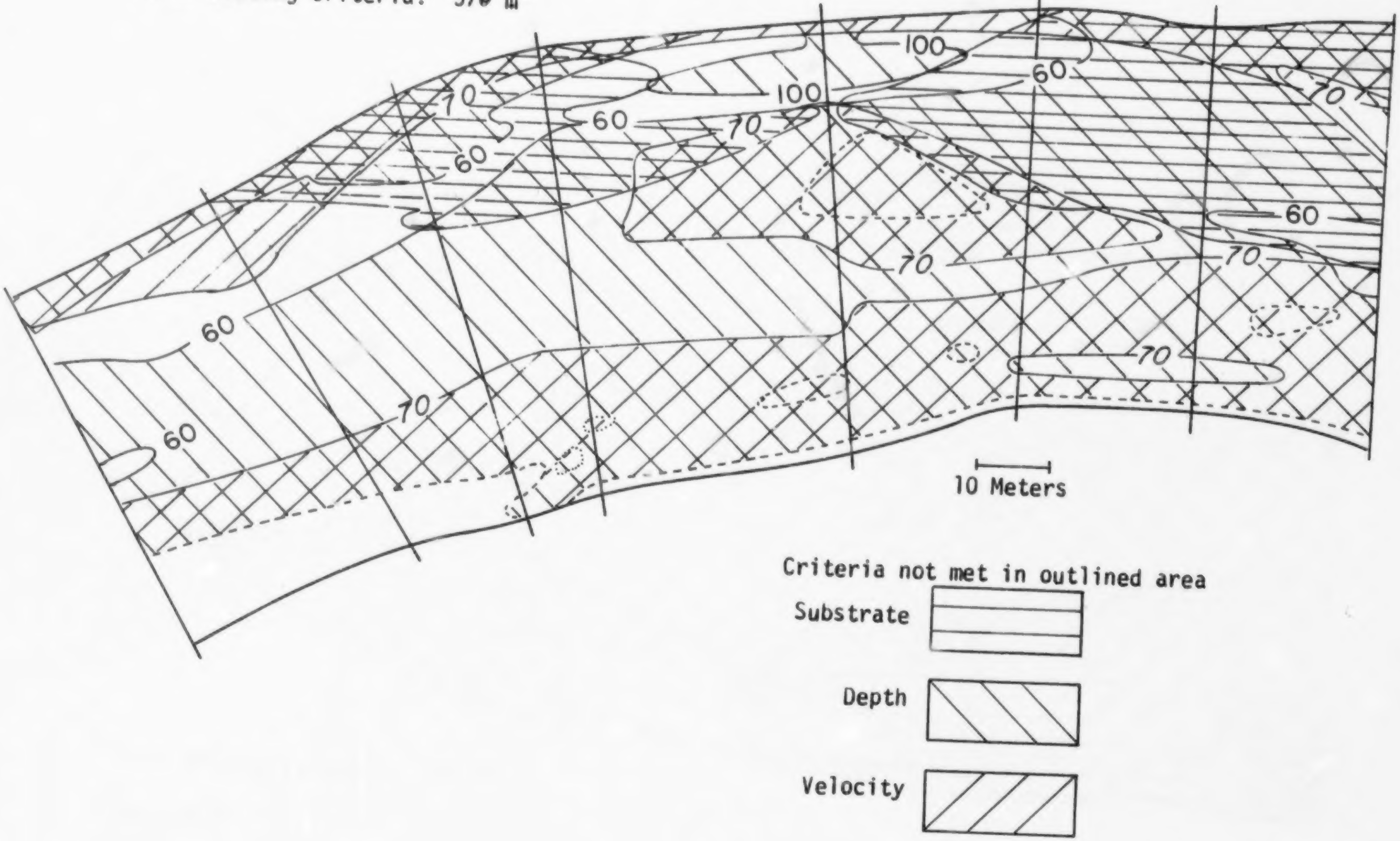
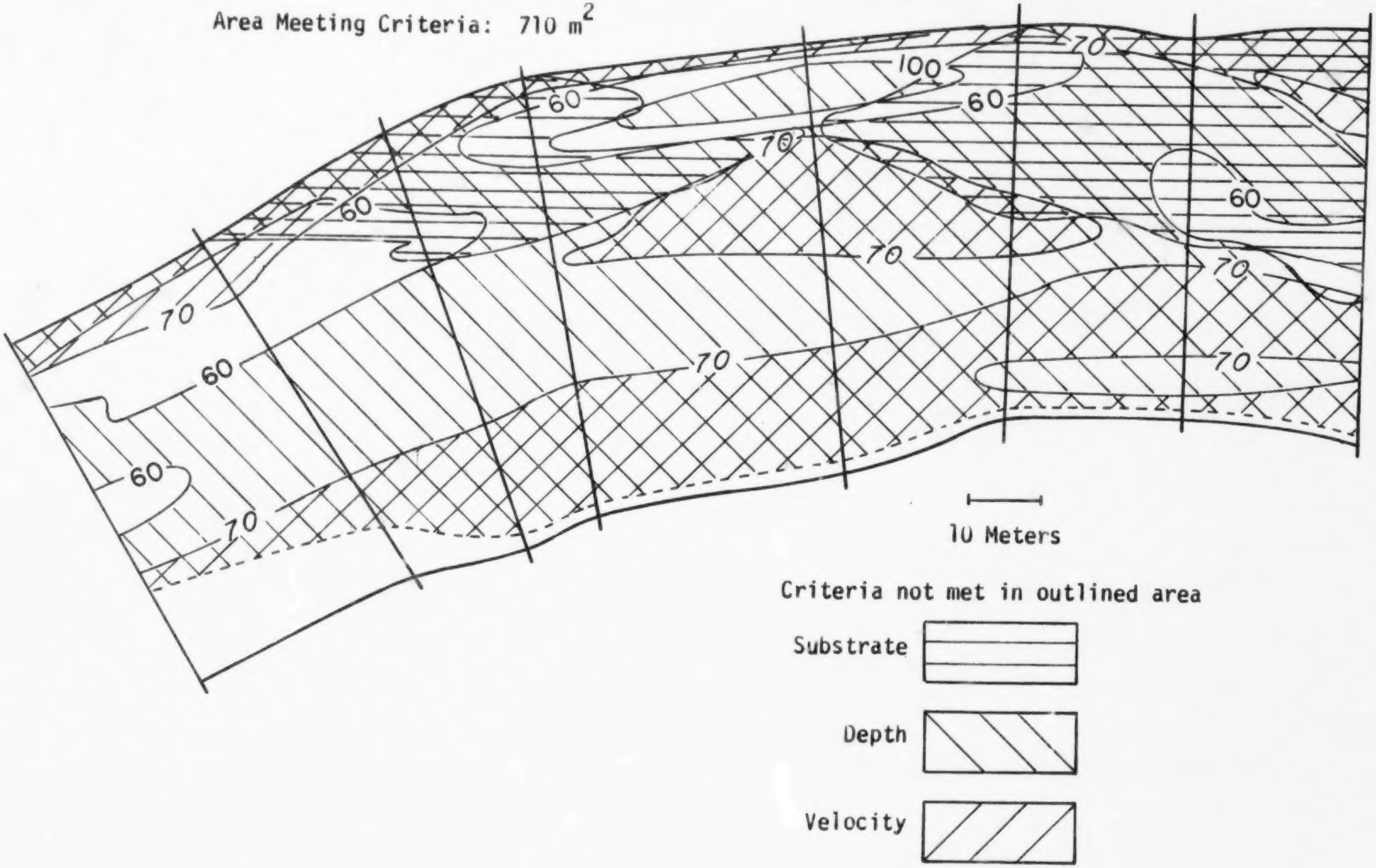


Figure F-4: Composite Map of the Ft. Keogh Spawning Section, Showing Areas Meeting Flow Criteria for Spawning Shovelnose Sturgeon.

Discharge: 18.1 cms.

Area Meeting Criteria: 710 m^2



[redacted]

Figure F-5: Composite Map of the Ft. Keogh Spawning Section, Showing Areas Meeting Flow Criteria for Spawning Shovelnose Sturgeon.

Discharge: 20.2 cms

Area Meeting Criteria: 870 m^2

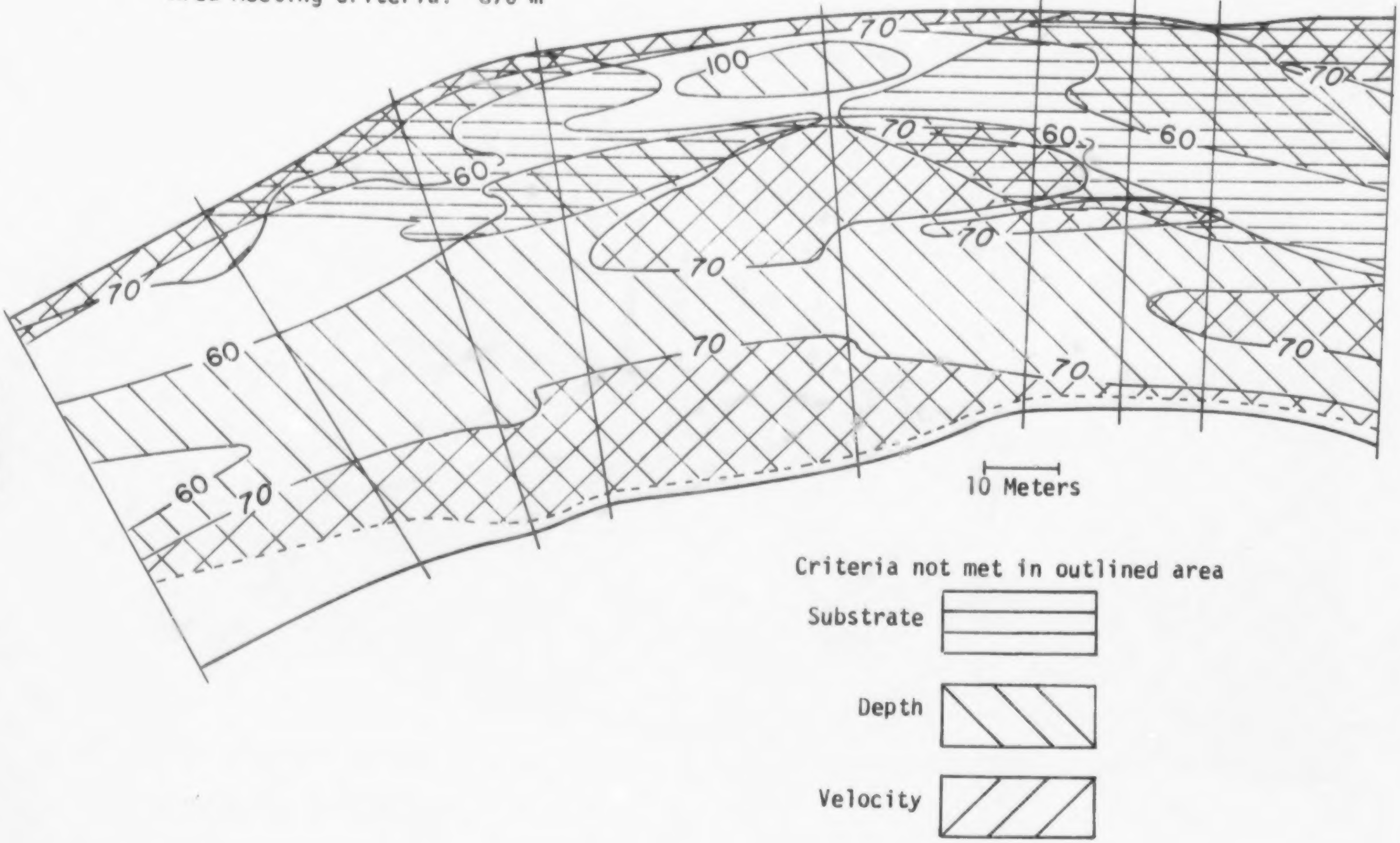


Figure F-6: Composite Map of the Ft. Keogh Spawning Section, Showing Areas Meeting Flow Criteria for Spawning Shovelnose Sturgeon.

Discharge: 22.5 cms.

Area Meeting Criteria: 1320 m^2

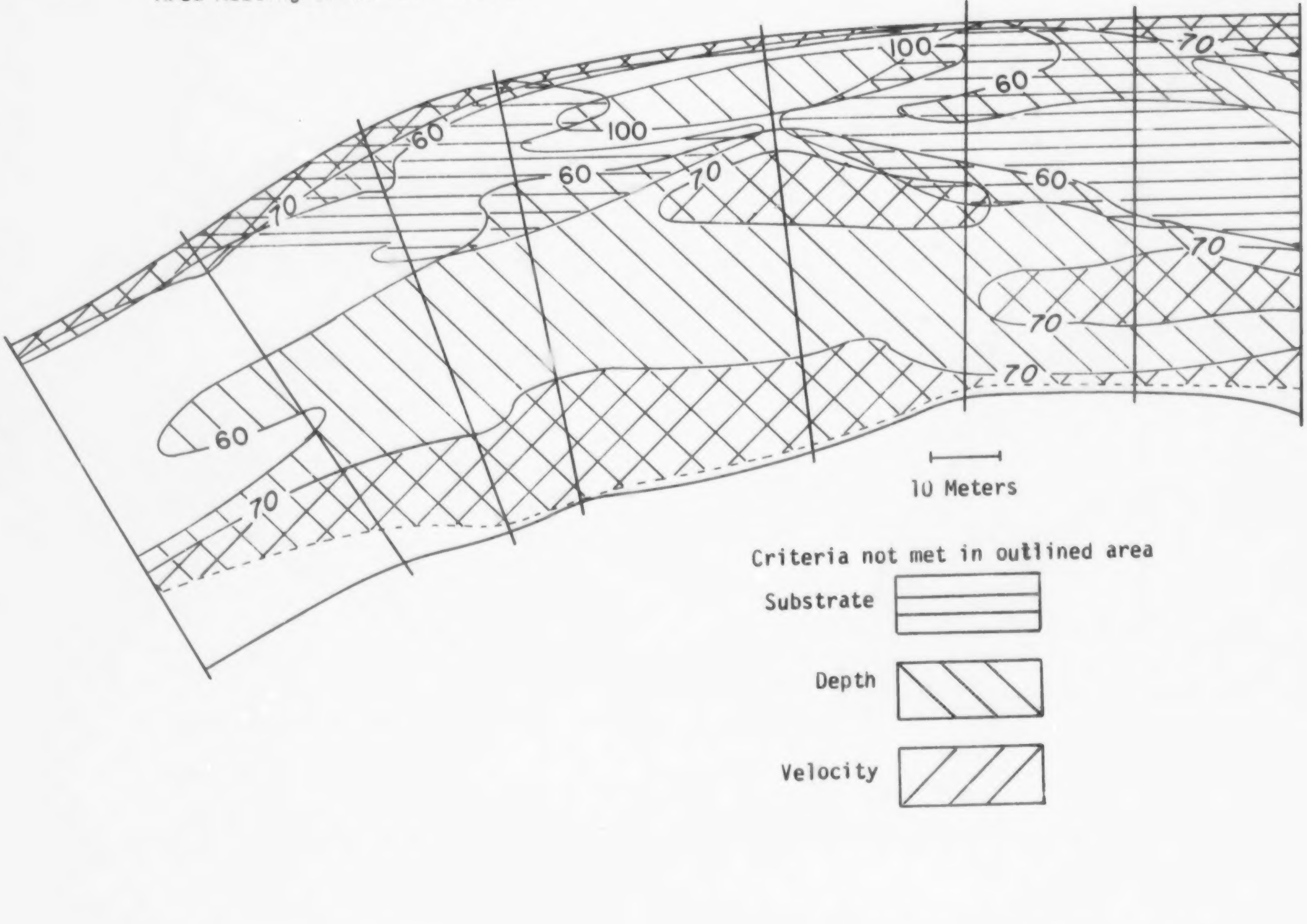


Figure F-7: Composite Map of the Ft. Keogh Spawning Section, Showing Areas Meeting Flow Criteria for Spawning Shovelnose Sturgeon.

Discharge: 25.5 cms.

Area Meeting Criteria: 1940 m^2

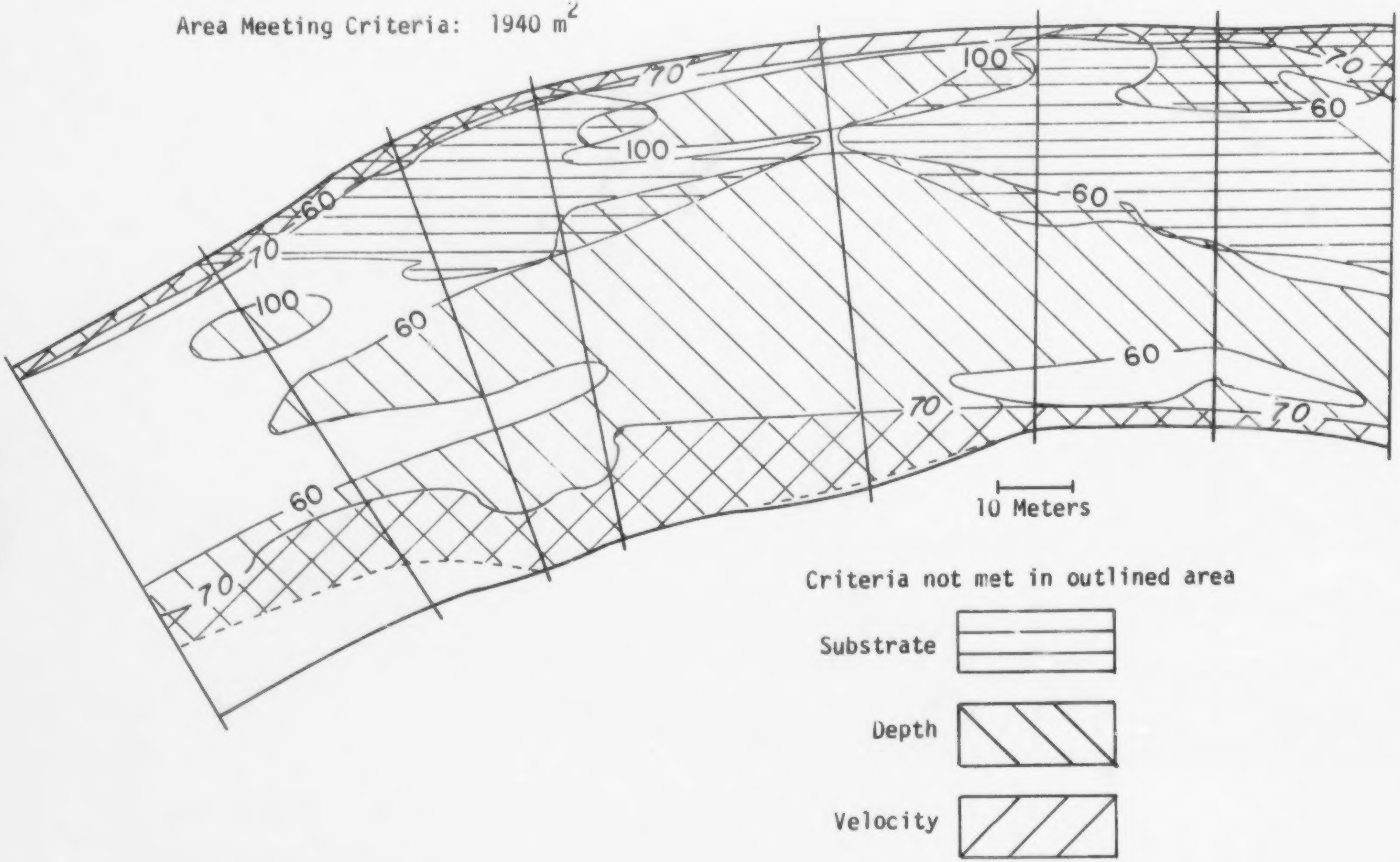
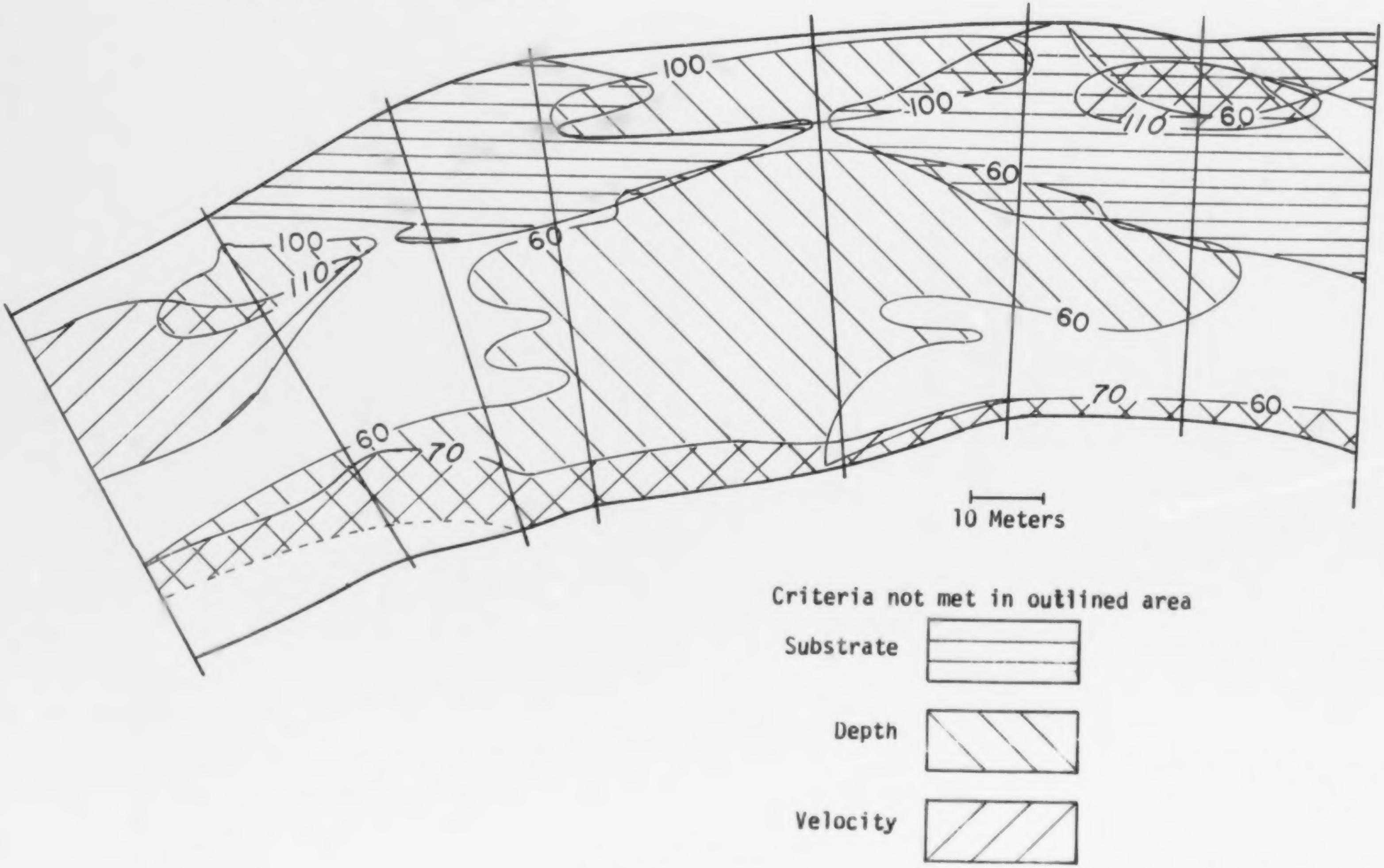


Figure F-8: Composite Map of the Ft. Keogh Spawning Section, Showing Areas Meeting Flow Criteria for Spawning Shovelnose Sturgeon.

Discharge: 28.3 cms.

Area Meeting Criteria: 2470 m^2



APPENDIX G

HYDROLOGIC CONTOUR MAPS

EXPERIMENTAL CHANNEL SECTION

1. This experimental channel was located in a side channel around a large island in the Viall Ranch section. Flow was manipulated by a diversion structure at the head of the island.

2. Direction of flow is from top of page to bottom.

3. For easier interpretation, depth contours are indicated by vertical typeface. Velocity contours are indicated by slanting typeface.

4. Hatchered areas on contour maps indicate isolated areas of reduced depth of velocity, depending on the type of map.

5. Dashed lines indicate edge of water, either at stream banks or on exposed bars.

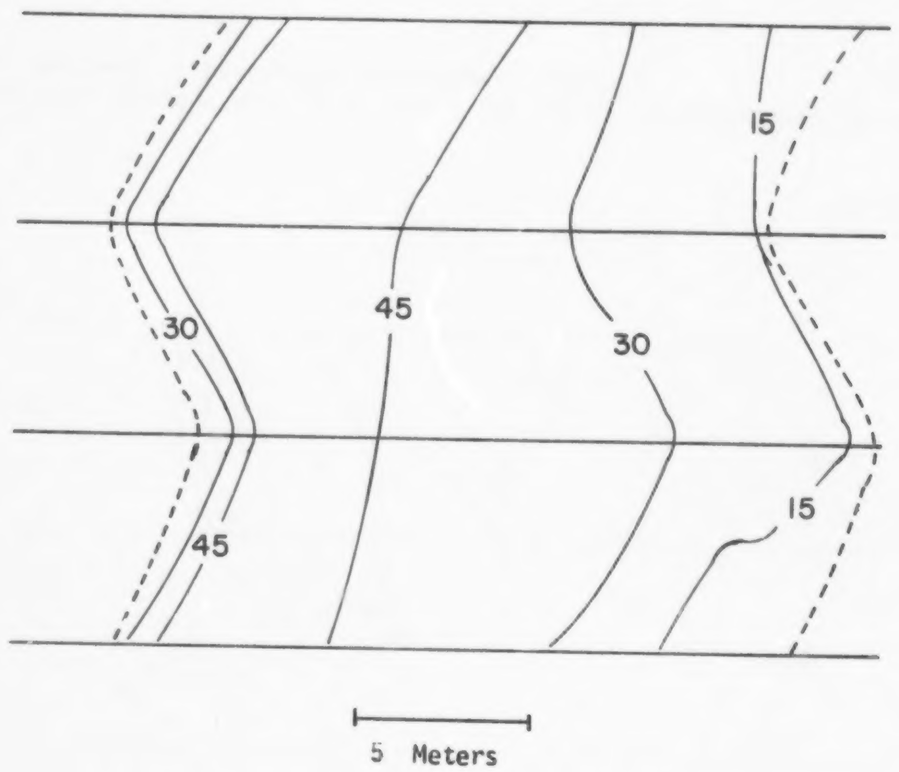


Figure G-1: Depth Contour Map for Riffle #1 of the Experimental Channel Section. Depths in cm. Experimental Discharge: 4.70 cms.

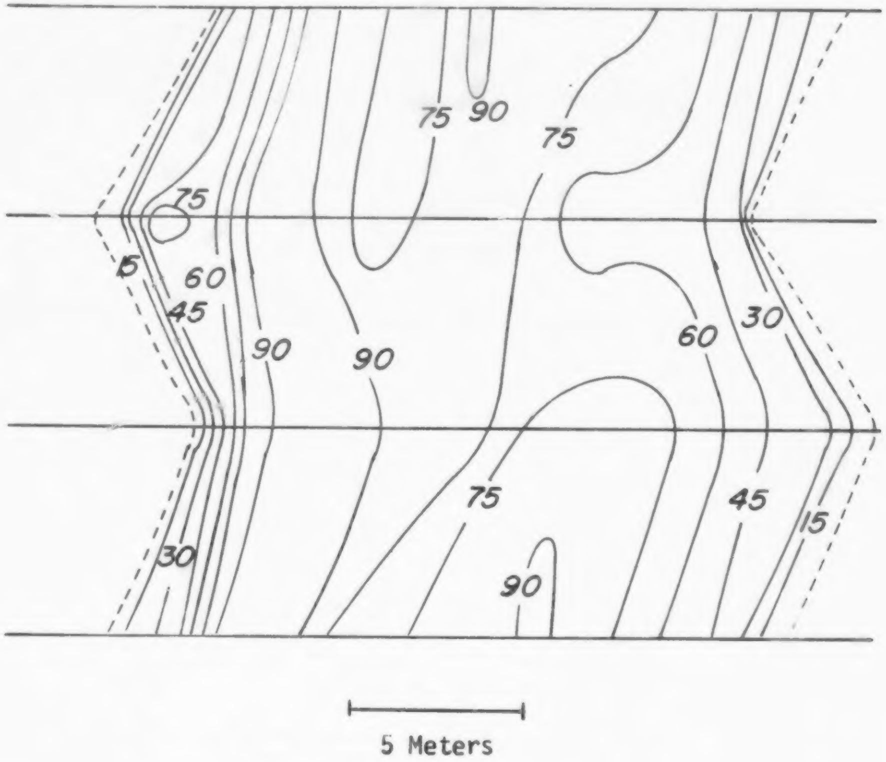


Figure G-2: Velocity Contour Map for Riffle #1 of the Experimental Channel Section. Velocities in cm./sec. Experimental Discharge: 4.70 cms.

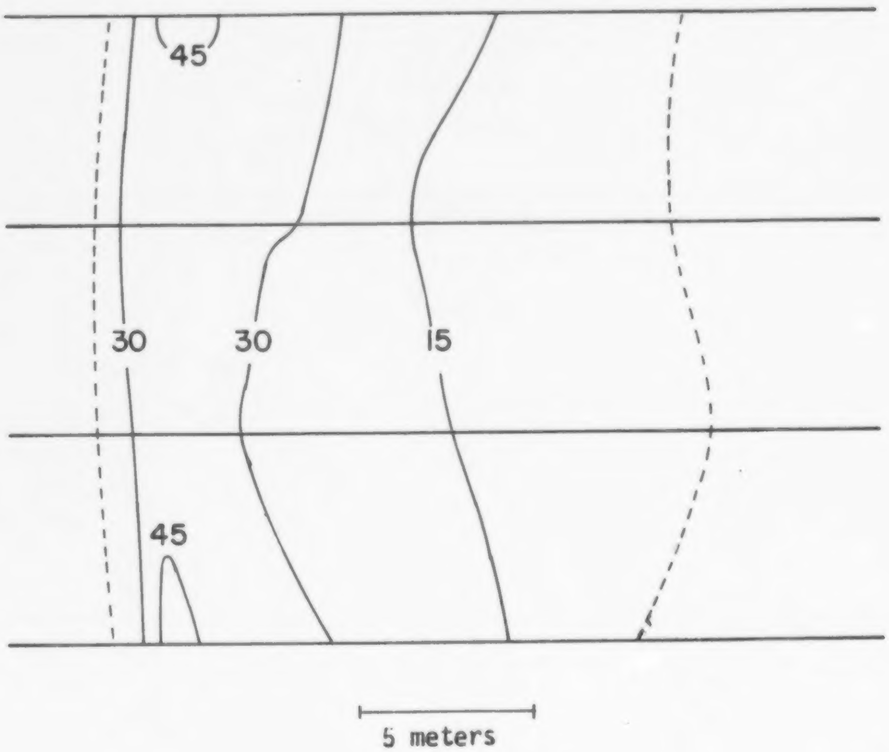


Figure G-3: Depth Contour Map for Riffle #1 of the Experimental Channel Section. Depths in cm. Experimental Discharge: 2.12 cms.

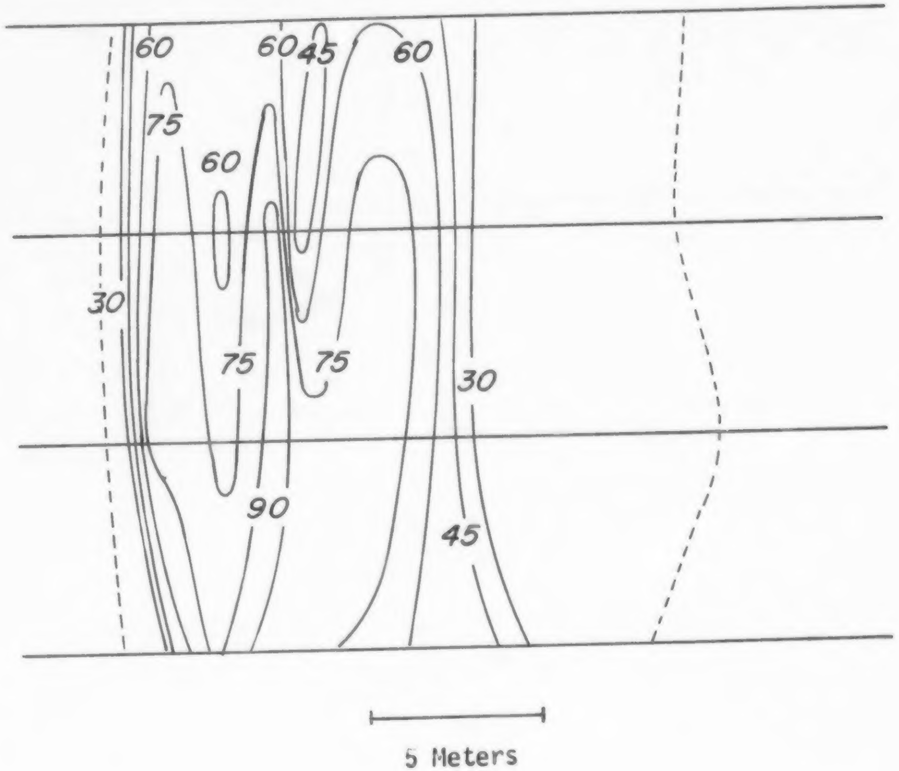


Figure G-4: Velocity Contour Map for Riffle #1 of the Experimental Channel Section. Velocities in cm./sec. Experimental Discharge: 2.12 cms.

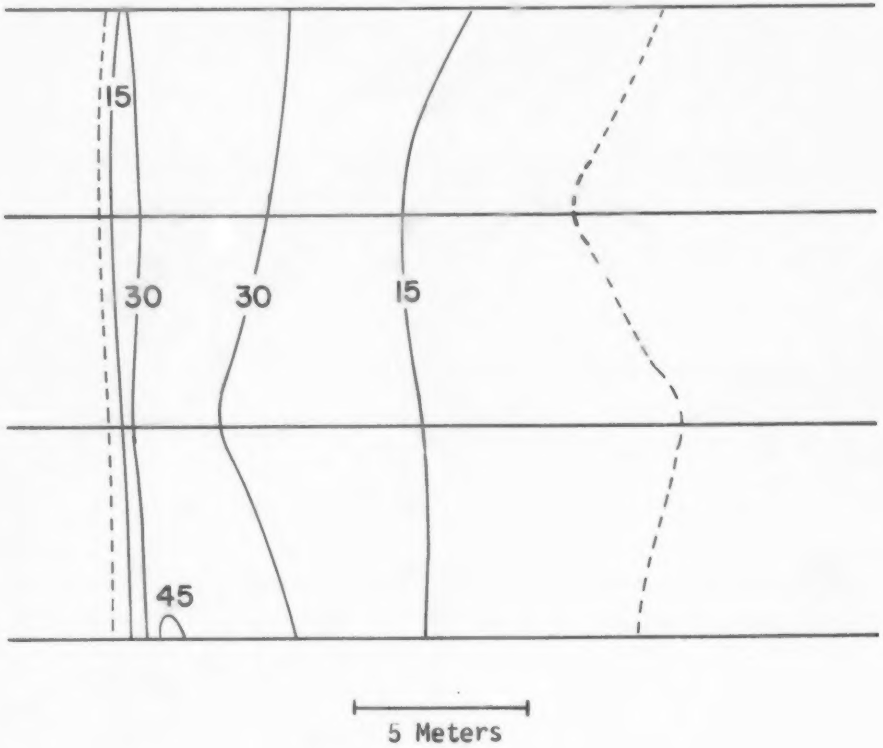


Figure G-5: Depth Contour Map for Riffle #1 of the Experimental Channel Section. Depths in cm. Experimental Discharge: 1.58 cms.

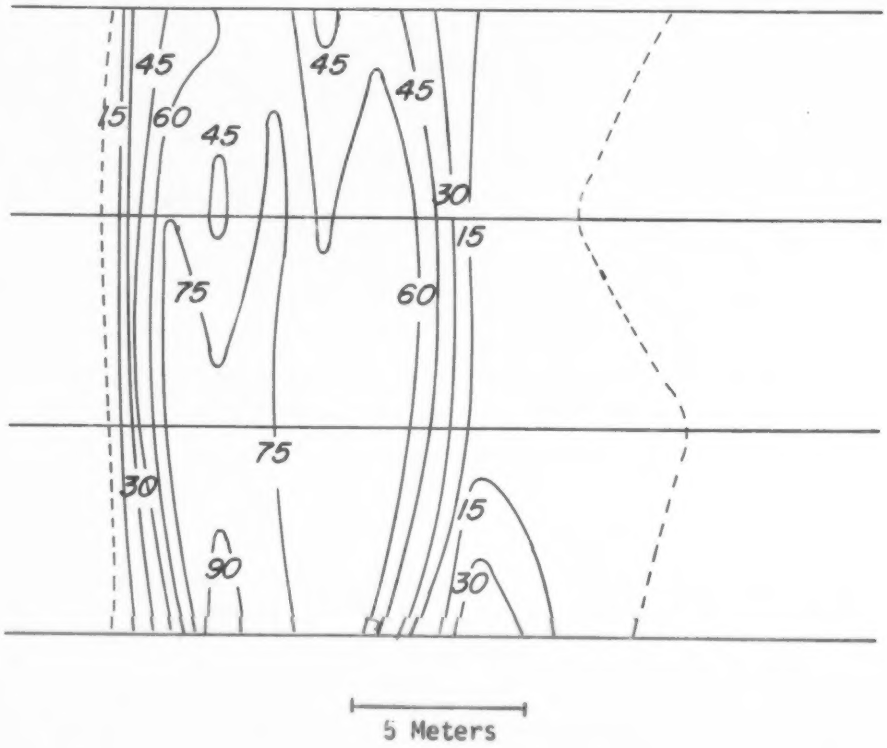


Figure G-6: Velocity Contour Map for Riffle #1 of the Experimental Channel Section. Velocities in cm./sec. Experimental Discharge: 1.58 cms.

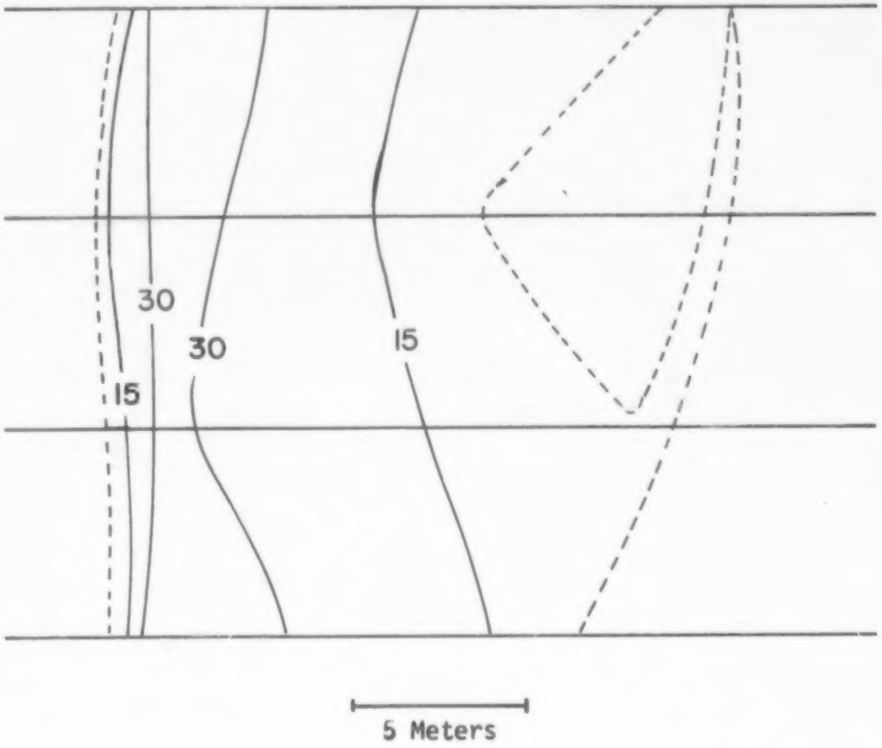


Figure G-7: Depth Contour Map for Riffle #1 of the Experimental Channel Section. Depths in cm. Experimental Discharge: 1.27 cms.

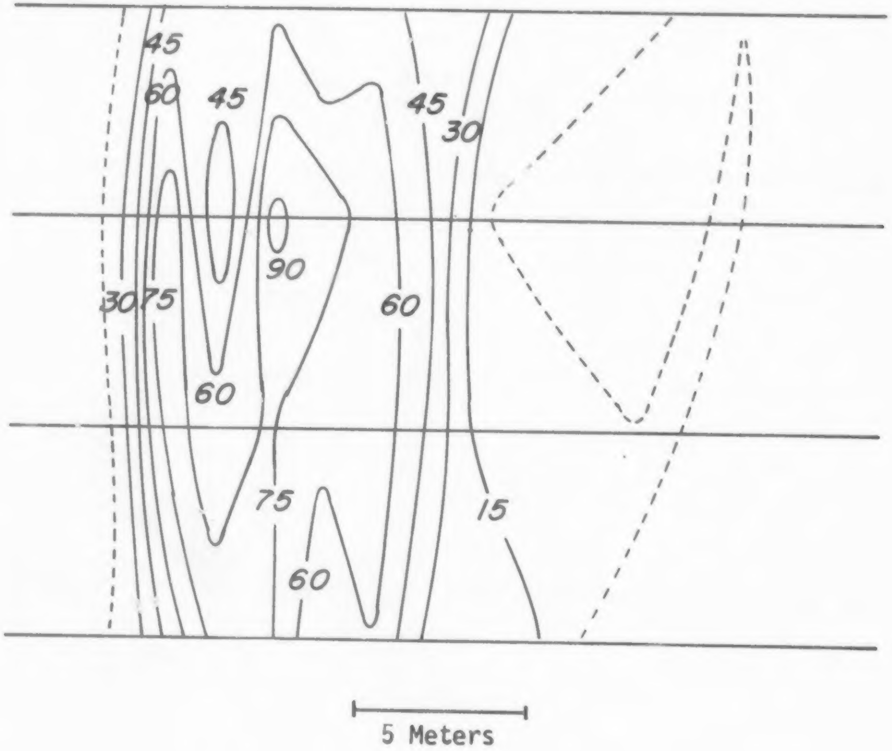


Figure G-8: Velocity Contour Map for Riffle #1 of the Experimental Channel Section. Velocities in cm./sec. Experimental Discharge: 1.27 cms.

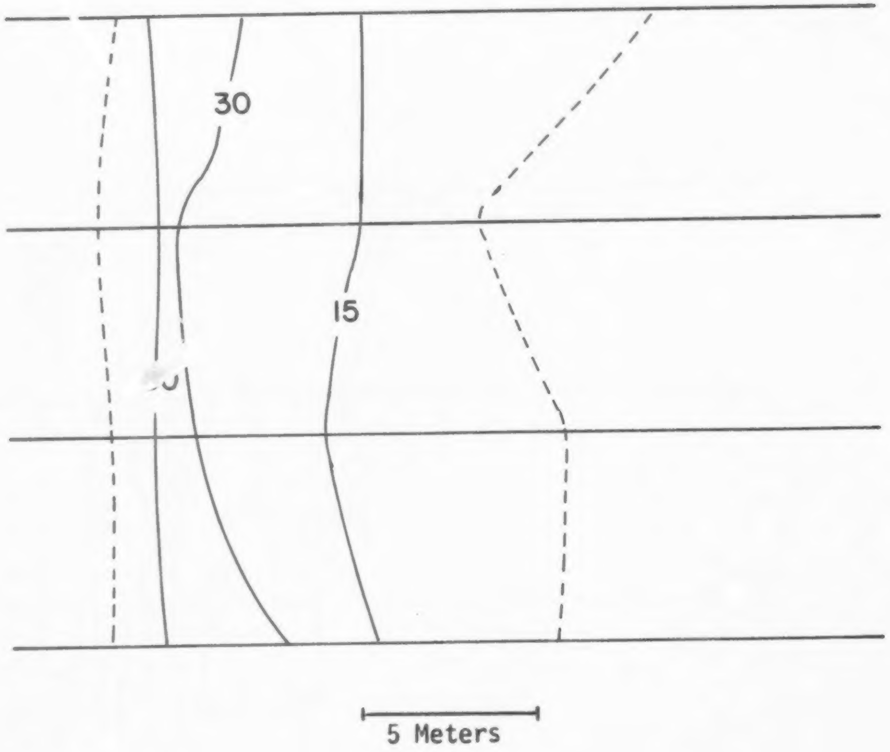


Figure G-9: Depth Contour Map for Riffle #1 of the Experimental Channel Section. Depths in cm. Experimental Discharge: 1.07 cms.

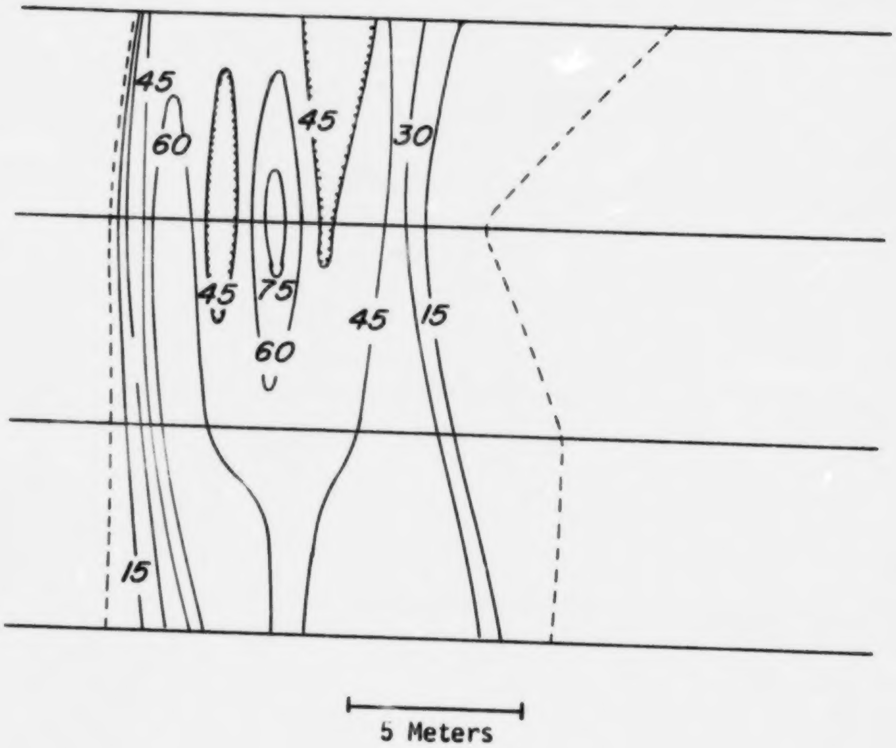


Figure G-10: Velocity Contour Map for Riffle #1 of the Experimental Channel Section. Velocities in cm./sec. Experimental Discharge: 1.07 cms.

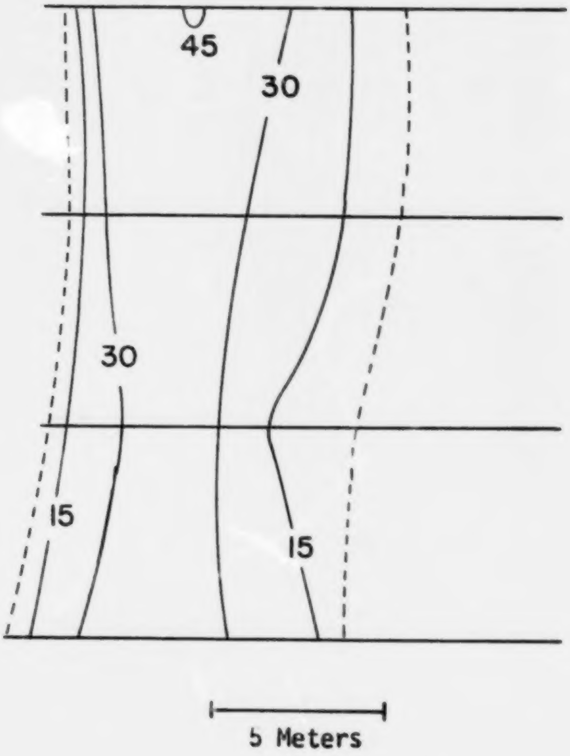


Figure G-11: Depth Contour Map for Riffle #2 of the Experimental Channel Section. Depths in cm. Experimental Discharge: 2.12 cms.

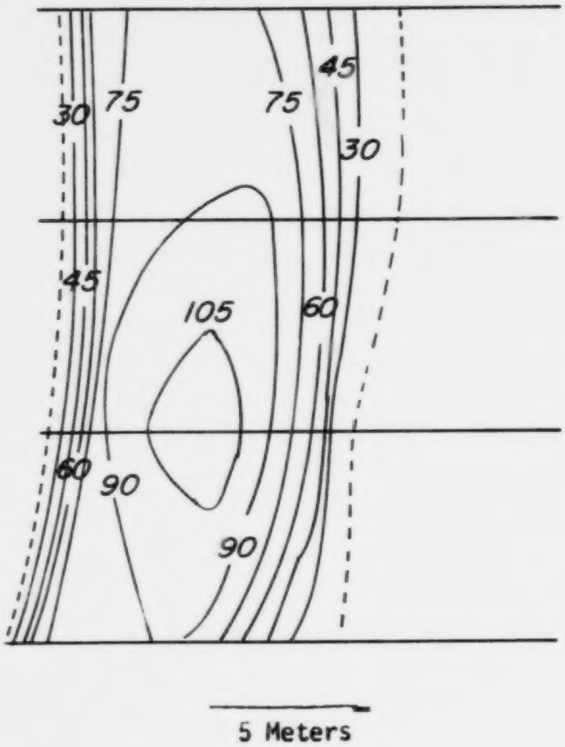


Figure G-12: Velocity Contour Map for Riffle #2 of the Experimental Channel Section. Velocities in cm./sec. Experimental Discharge: 2.12 cms.

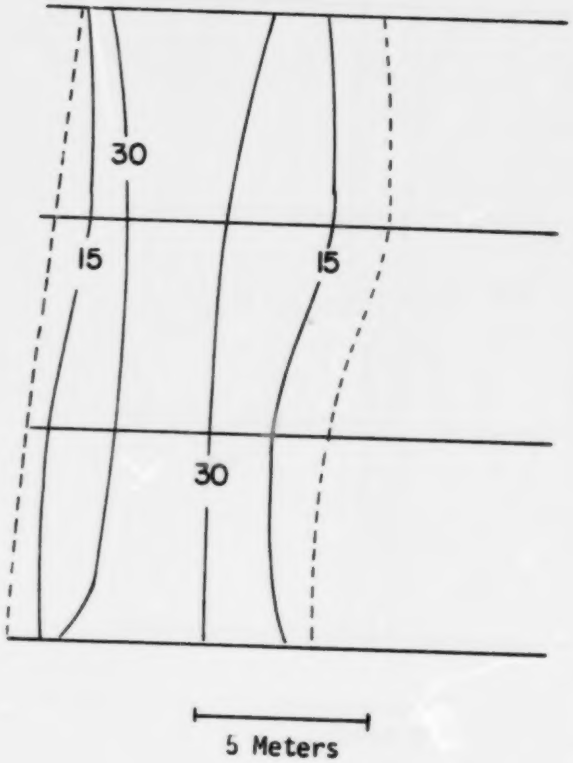


Figure G-13: Depth Contour Map for Riffle #2 of the Experimental Channel Section. Depths in cm. Experimental Discharge: 1.47 cms.

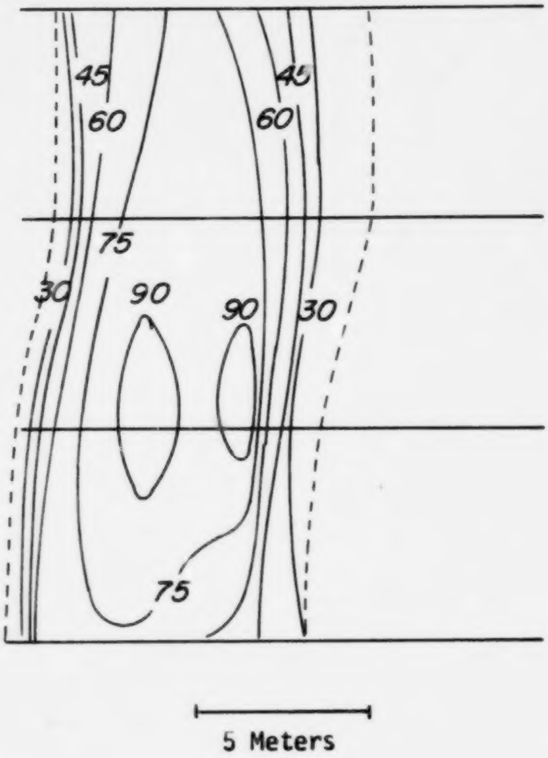


Figure G-14: Velocity Contour Map for Riffle #2 of the Experimental Channel Section. Velocities in cm./sec. Experimental Discharge: 1.47 cms.

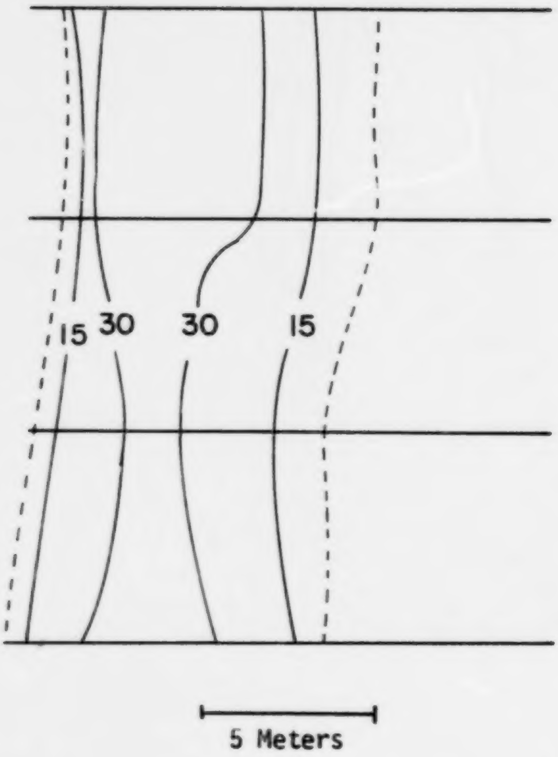


Figure G-15: Depth Contour Map for Riffle #2 of the Experimental Channel Section. Depths in cm. Experimental Discharge: 1.33 cms.

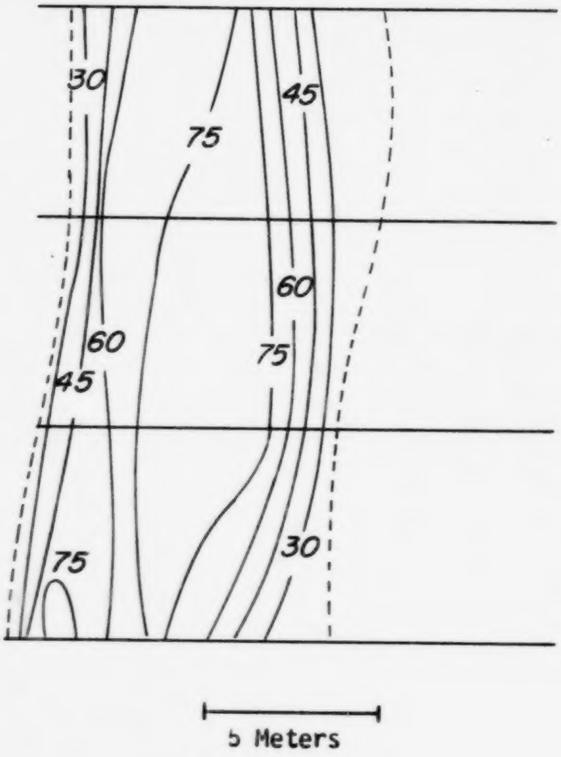


Figure G-16: Velocity Contour Map for Riffle #2 of the Experimental Channel Section. Velocities in cm./sec. Experimental Discharge: 1.33 cms.

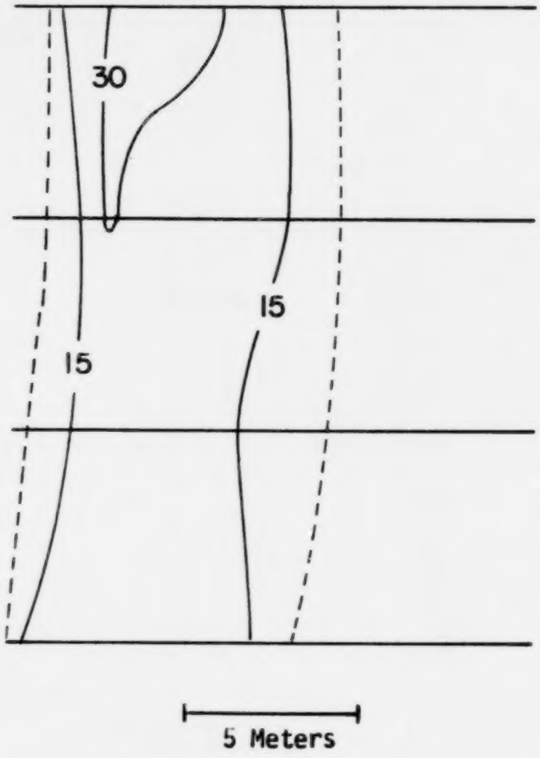


Figure G-17: Depth Contour Map for Riffle #2 of the Experimental Channel Section. Depths in cm. Experimental Discharge: 1.08 cms.

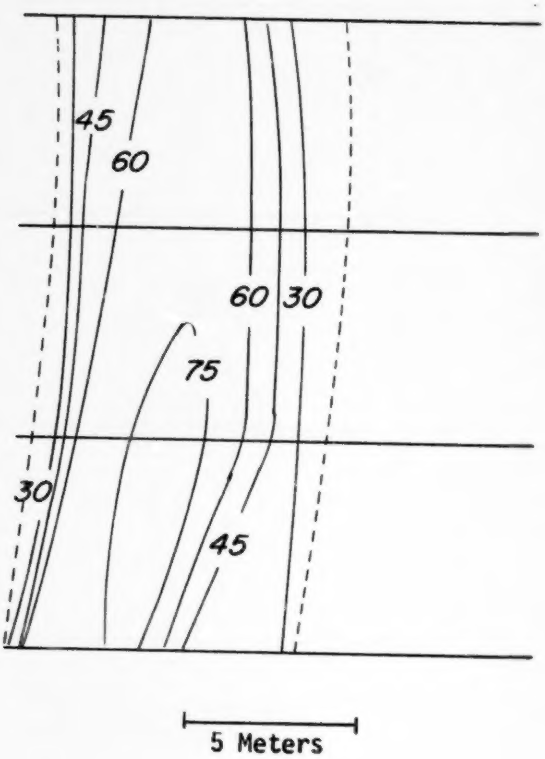


Figure G-18: Velocity Contour Map for Riffle #2 of the Experimental Channel Section. Velocities in cm./sec. Experimental Discharge: 1.08 cms.

APPENDIX H

COMPOSITE MAPS

EXPERIMENTAL CHANNEL SECTION

1. This experimental channel was located in a side channel around a large island in the Viall Ranch section. Flow was minipulated by a diversion structure at the head of the island.

2. Direction of flow is from top of page to bottom.

3. For easier interpretation, depth contours are indicated by vertical typeface. Velocity contours are indicated by slanting typeface.

4. Cross-hatched areas on composite maps indicate areas which do not meet flow criteria for the stonecat. Only those stream areas without cross-hatching meet flow criteria.

5. Dashed lines indicate water's edge, either at banks or on exposed bars.

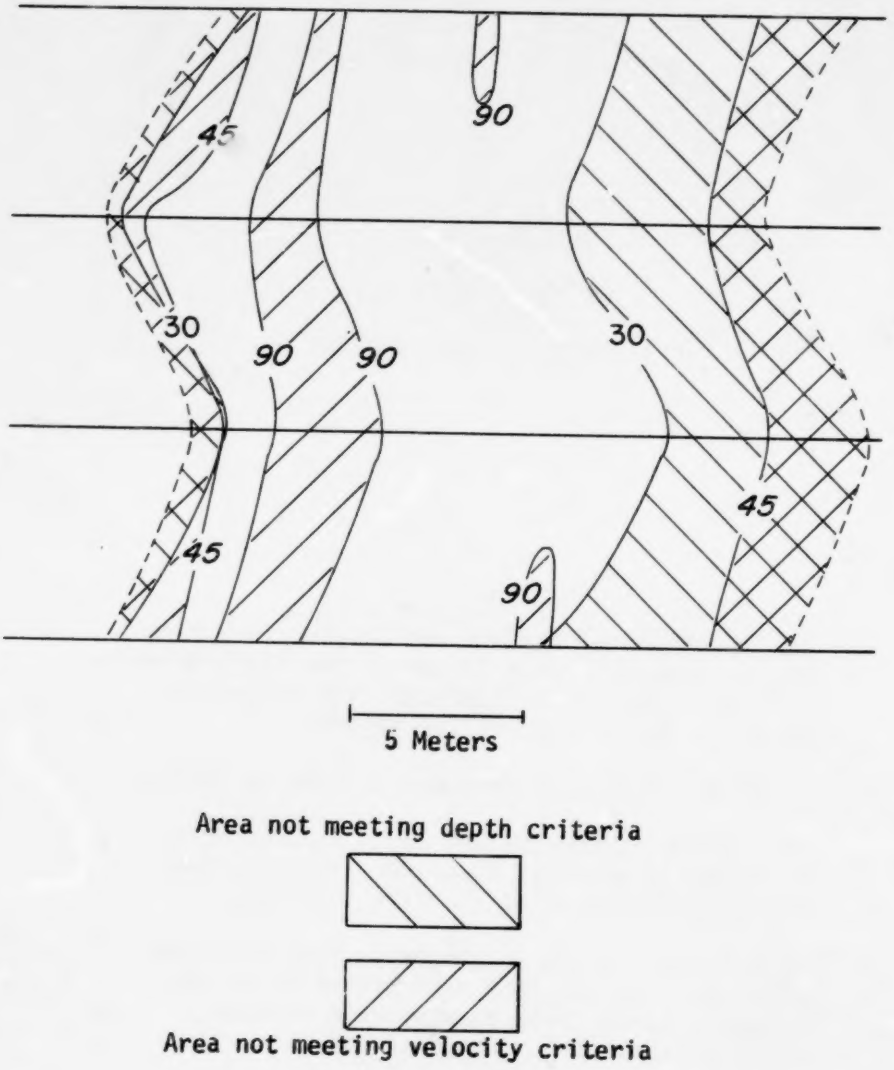

45
90
30
90
90
30
45
45
90
5 Meters
Area not meeting depth criteria
Area not meeting velocity criteria

Figure H-1: Composite Map for Riffle #1 of the Experimental Channel Section, Showing Areas Meeting Flow Criteria for the Stonecat. Experimental Discharge: 4.70 cms. Area Meeting Criteria: 163 square meters.

[redacted]

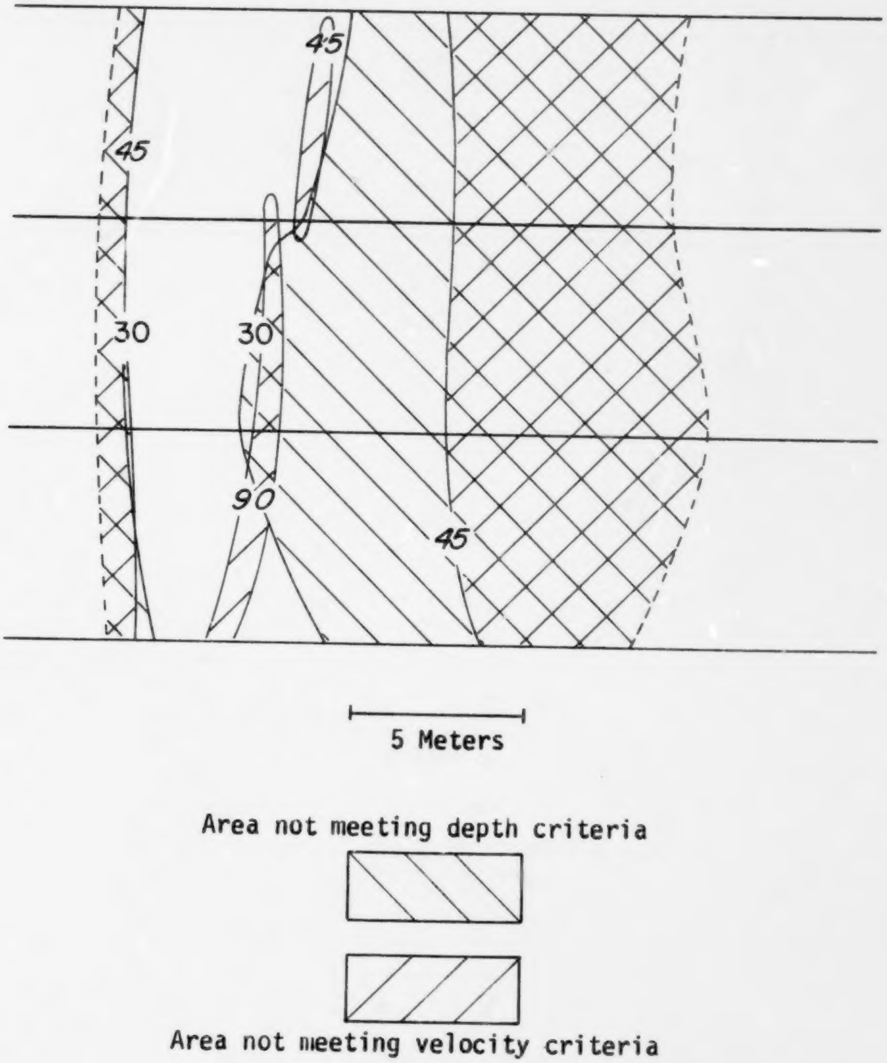

45
45
30
30
90
45
5 Meters
Area not meeting depth criteria
▧
▨
Area not meeting velocity criteria

Figure H-2: Composite Map for Riffle #1 of the Experimental Channel Section, Showing Areas Meeting Flow Criteria for the Stonecat. Experimental Discharge: 2.12 cms. Area Meeting Criteria: 72 square meters.

[redacted]

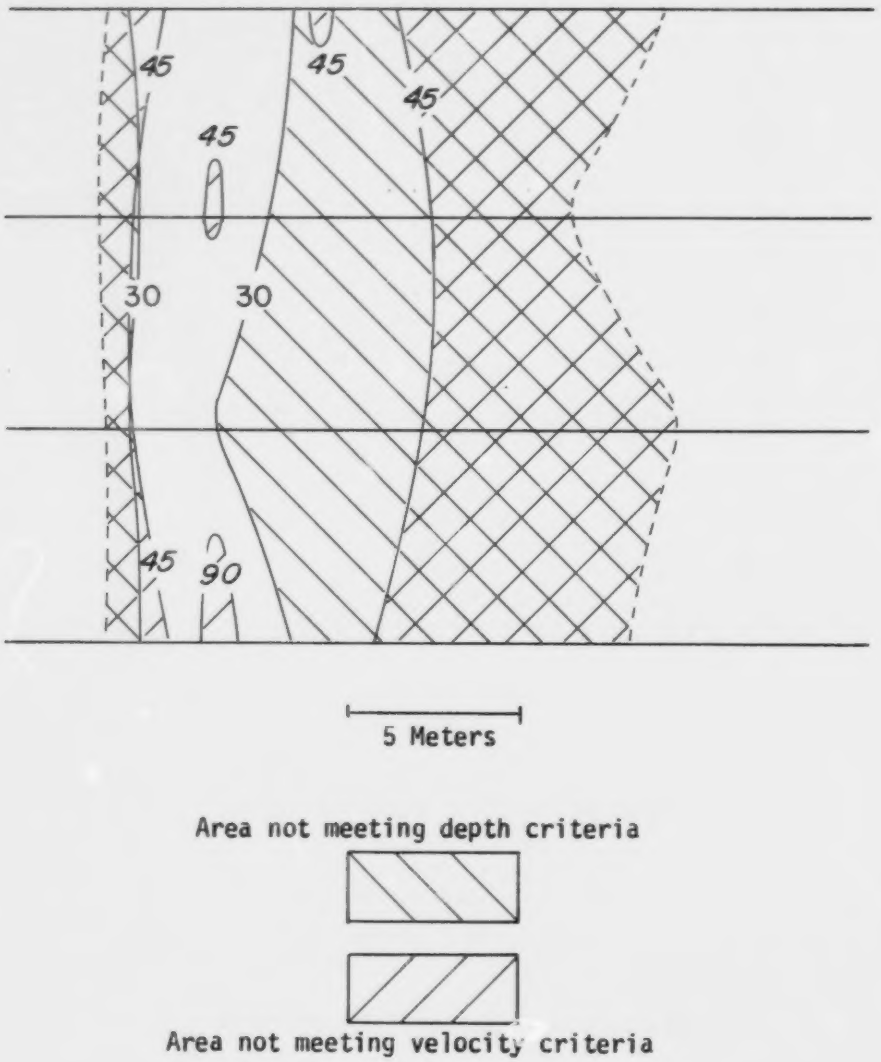

45
45
45
45
30
30
45
90
5 Meters
Area not meeting depth criteria
Area not meeting velocity criteria

Figure H-3: Composite Map for Riffle #1 of the Experimental Channel Section, Showing Areas Meeting Flow Criteria for the Stonecat. Experimental Discharge: 1.58 cms. Area Meeting Criteria: 59 square meters.

[redacted]

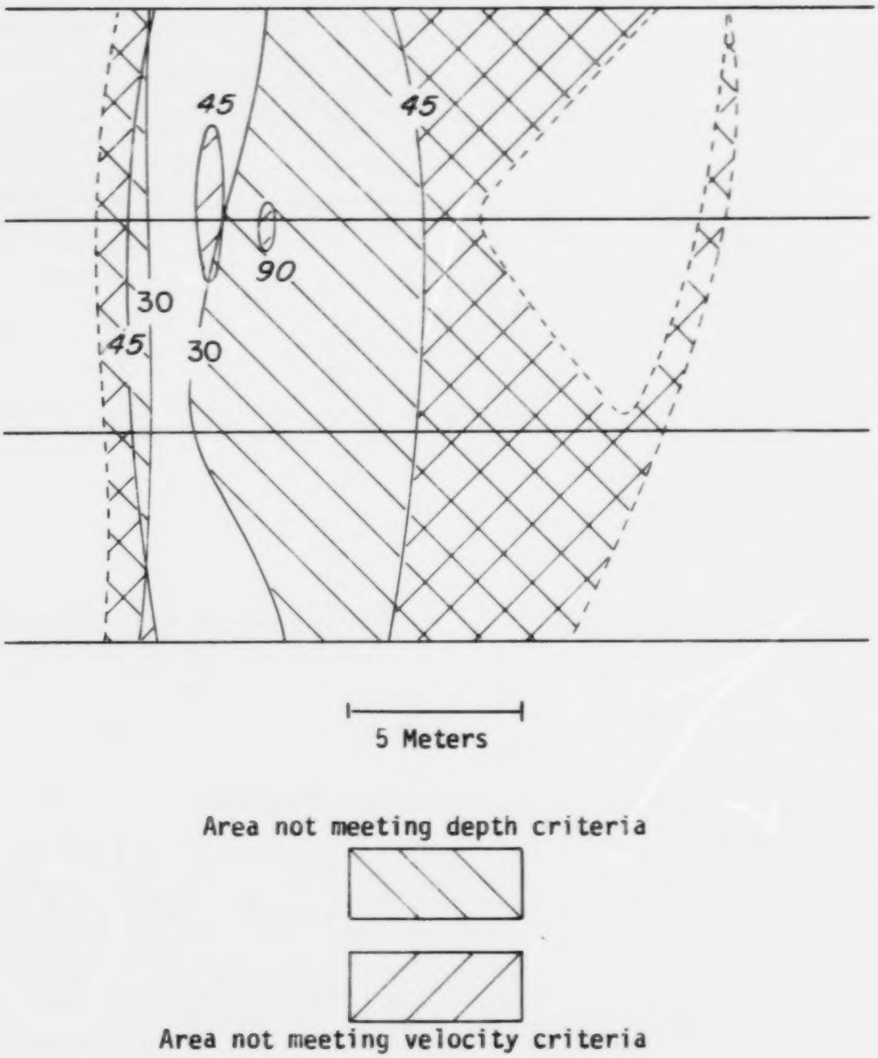

45
45
90
30
45
30
5 Meters
Area not meeting depth criteria
Area not meeting velocity criteria

Figure H-4: Composite Map for Riffle #1 of the Experimental Channel Section, Showing Areas Meeting Flow Criteria for the Stonecat. Experimental Discharge: 1.27 cms. Area Meeting Criteria: 39 square meters.

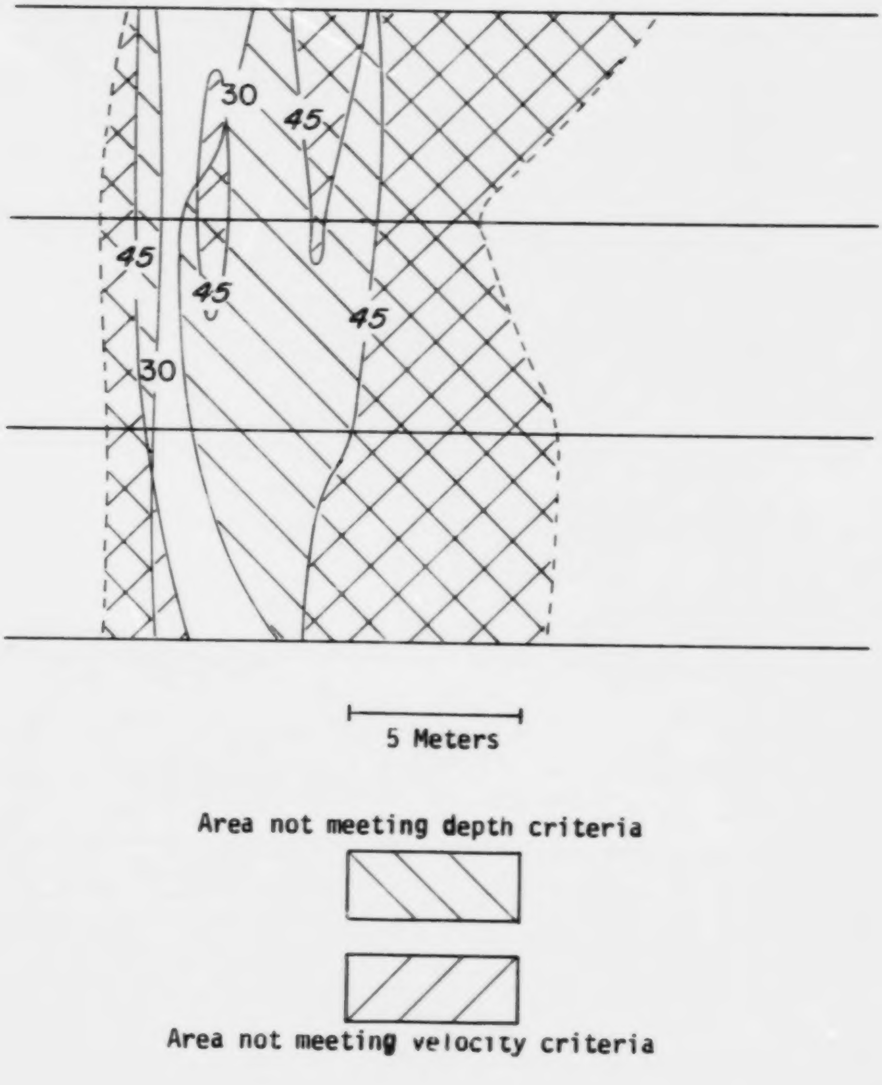

30
45
45
45
45
45
30
5 Meters
Area not meeting depth criteria
Area not meeting velocity criteria

Figure H-5: Composite Map for Riffle #1 of the Experimental Channel Section, Showing Areas Meeting Flow Criteria for the Stonecat. Experimental Discharge: 1.07 cms. Area Meeting Criteria: 27 square meters.

[redacted]

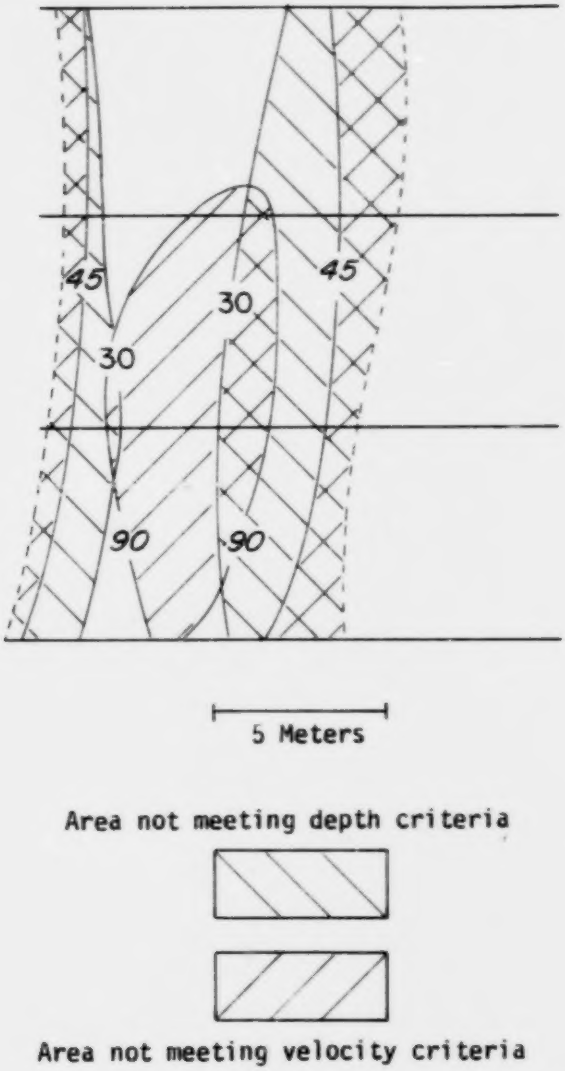

45
45
30
30
30
90
90
5 Meters
Area not meeting depth criteria
Area not meeting velocity criteria

Figure H-6: Composite Map for Riffle #2 of the Experimental Channel Section, Showing Areas meeting Flow Criteria for the Stonecat. Experimental Discharge: 2.12 cms. Area Meeting Criteria: 36 square meters.

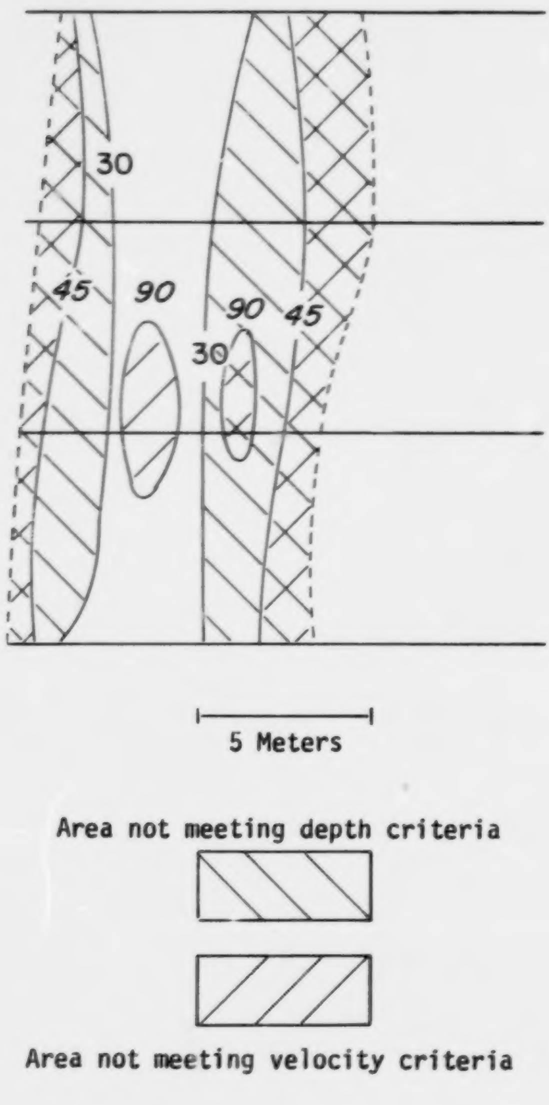

30
45
90
30
90
45
5 Meters
Area not meeting depth criteria
Area not meeting velocity criteria

Figure H-7: Composite Map for Riffle #2 of the Experimental Channel Section, Showing Areas Meeting Flow Criteria for the Stonecat. Experimental Discharge: 1.58 cms. Area Meeting Criteria: 53 square meters.

[redacted]

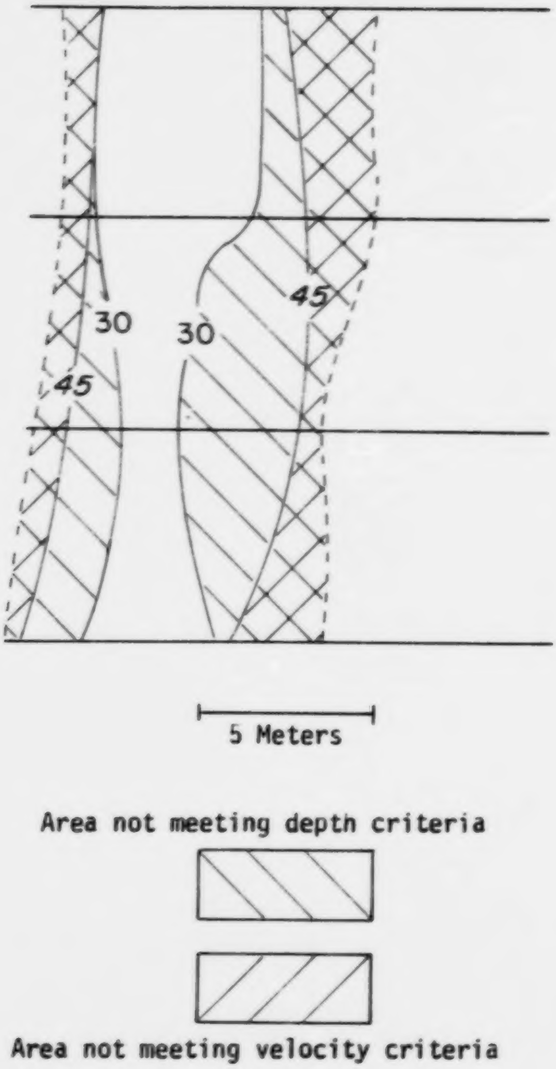

30
30
45
45
5 Meters
Area not meeting depth criteria
Area not meeting velocity criteria

Figure H-8: Composite Map for Riffle #2 of the Experimental Channel Section, Showing Areas Meeting Flow Criteria for the Stonecat. Experimental Discharge: 1.33 cms. Area Meeting Criteria: 60 square meters.

[redacted]

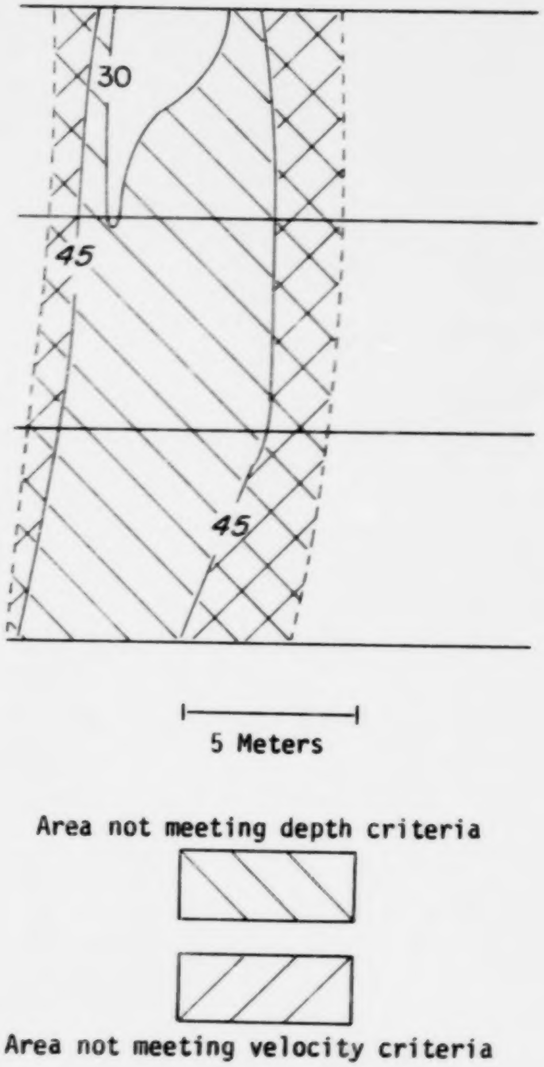

30
45
45
5 Meters
Area not meeting depth criteria
Area not meeting velocity criteria

Figure H-9: Composite Map for Riffle #2 of the Experimental Channel Section, Showing Areas Meeting Flow Criteria for the Stonecat. Experimental Discharge: 1.07 cms. Area Meeting Criteria: 11 square meters.

APPENDIX I

ICE FORMATION CROSS SECTIONAL DIAGRAMS

1. Cross hatched areas indicate surface ice sheet

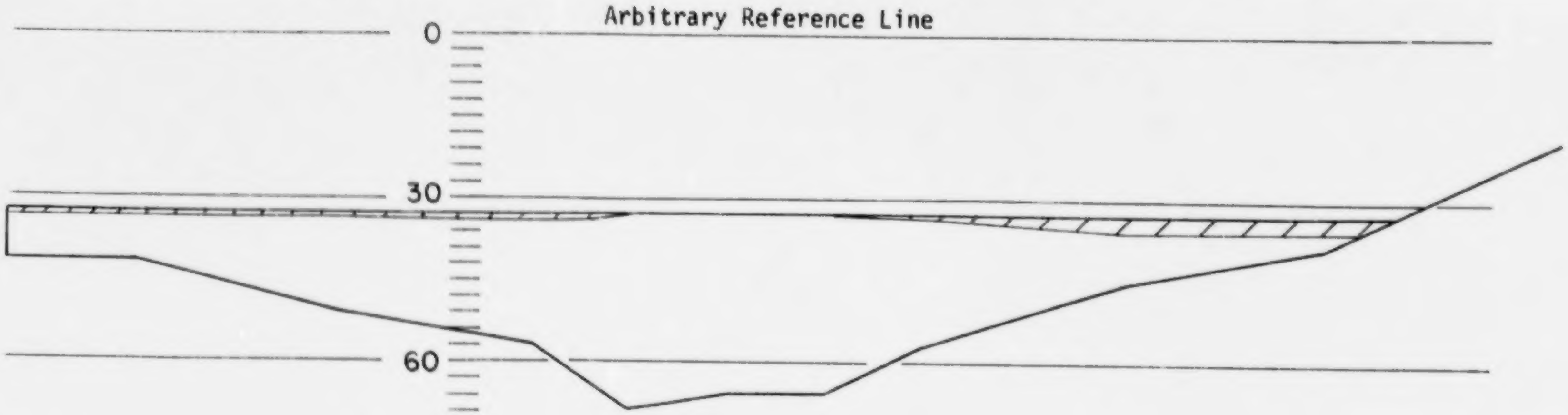


Figure I-1a: Cross-sectional view of channel and surface ice sheet at transect 1, Orcutt Ranch Section, 11/20/75. Vertical scale in cm. below arbitrary datum.

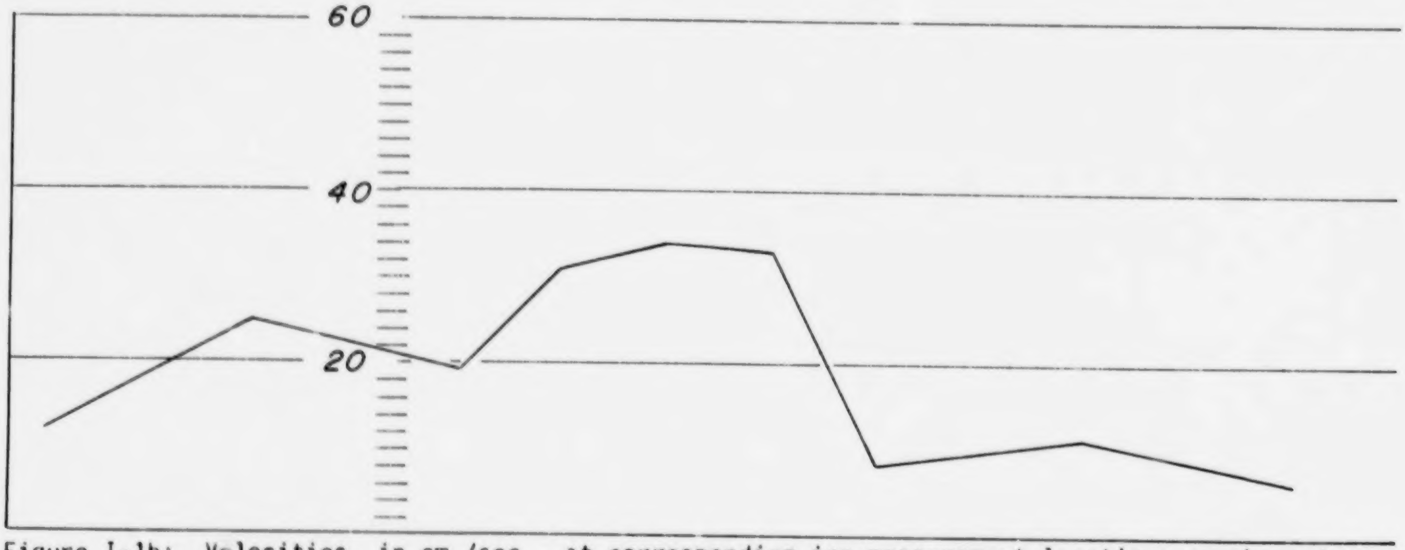


Figure I-1b: Velocities, in cm./sec., at corresponding ice measurement locations on above transect.

[redacted]

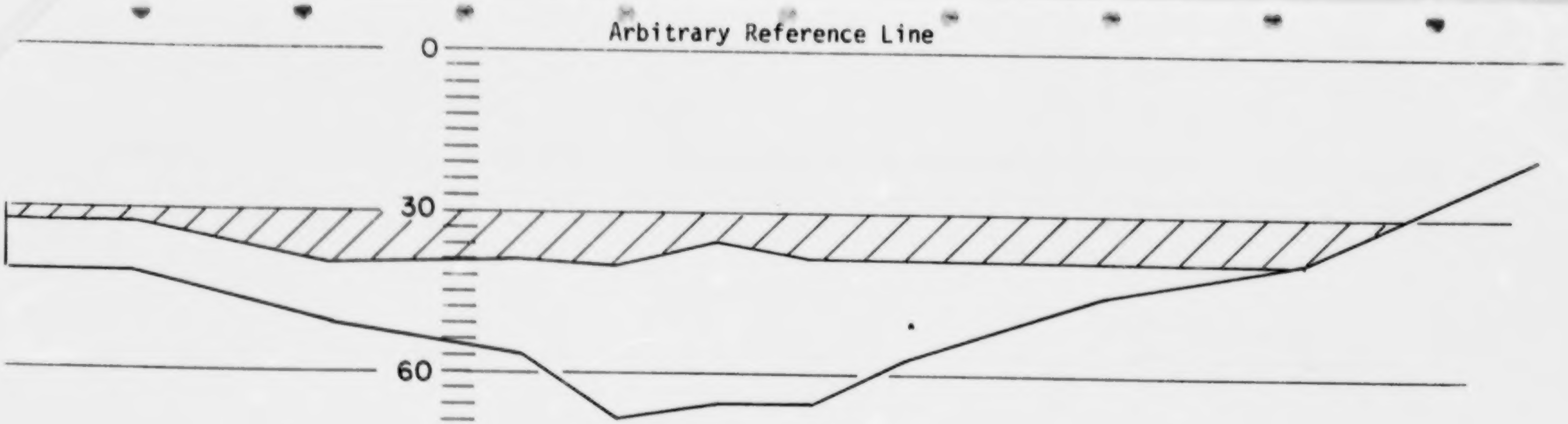


Figure I-2a: Cross-sectional view of channel and surface ice sheet at transect 1, Orcutt Ranch Section, 11/26/75. Vertical scale in cm. below arbitrary datum.

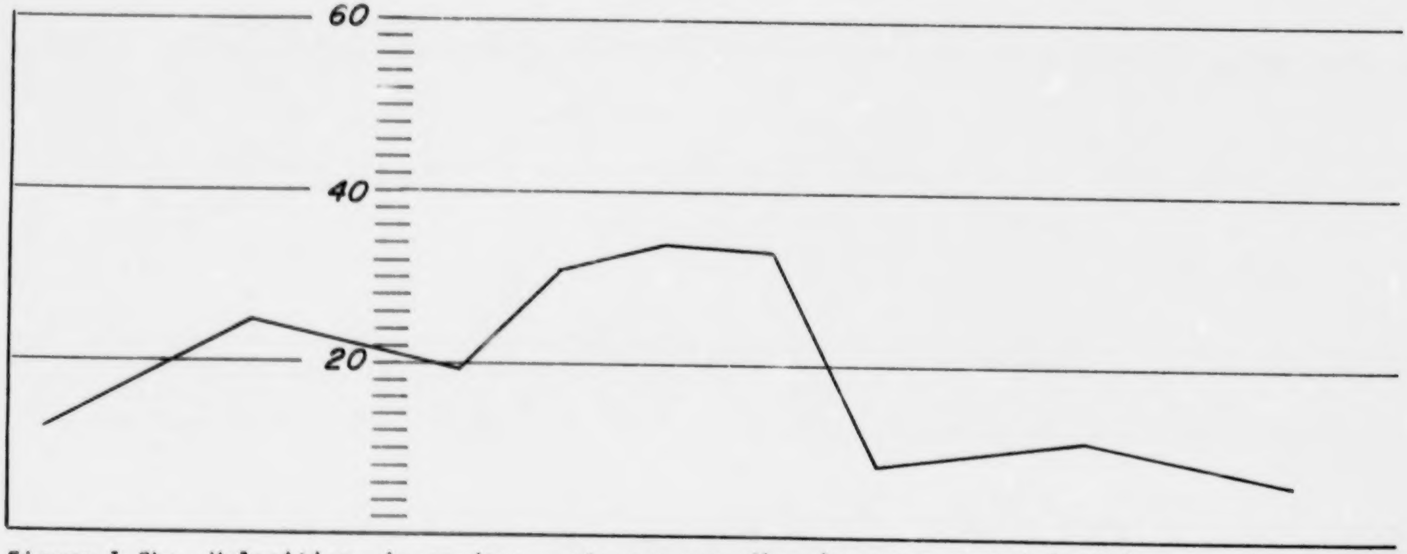


Figure I-2b: Velocities, in cm./sec., at corresponding ice measurement locations on above transect.

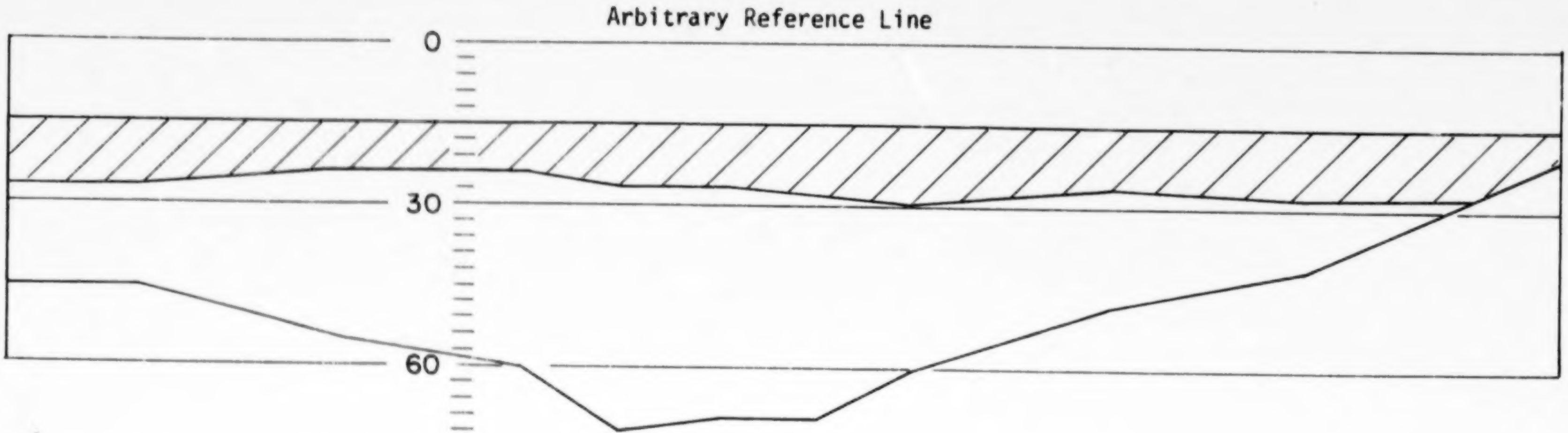


Figure I-3a: Cross-sectional view of channel and surface ice sheet at transect 1, Orcutt Ranch Section, 12/4/75. Vertical scale in cm. below arbitrary datum.

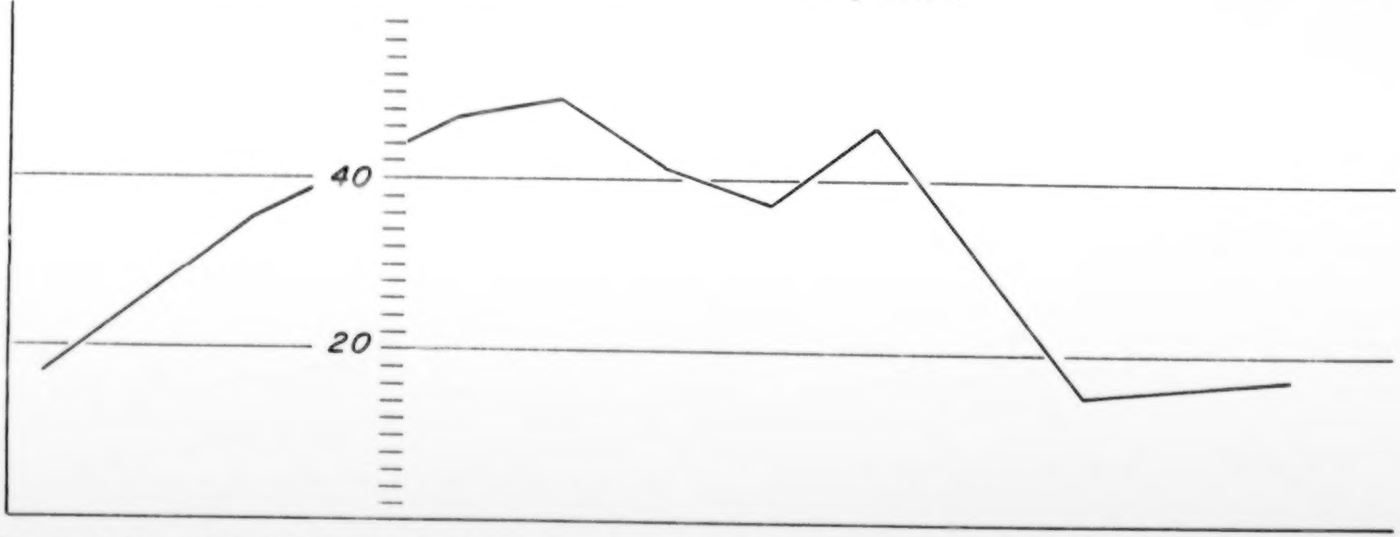


Figure I-3b: Velocities, in cm./sec., at corresponding ice measurement locations on above transect.

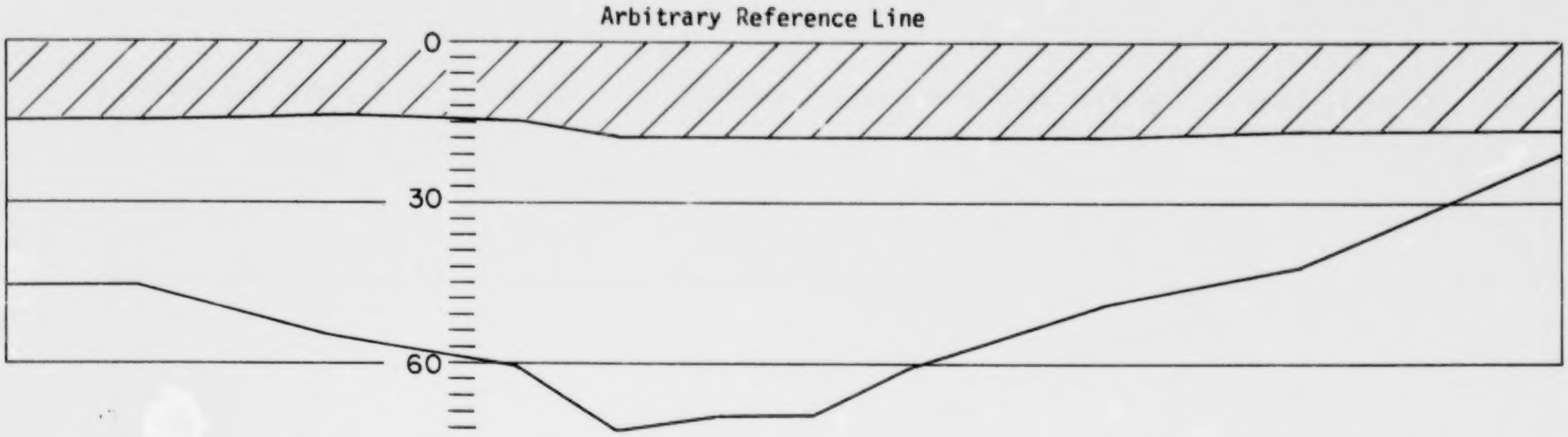


Figure I-4a: Cross-sectional view of channel and surface ice sheet at transect 1, Orcutt Ranch Section, 12/23/75. Vertical scale in cm. below arbitrary datum.

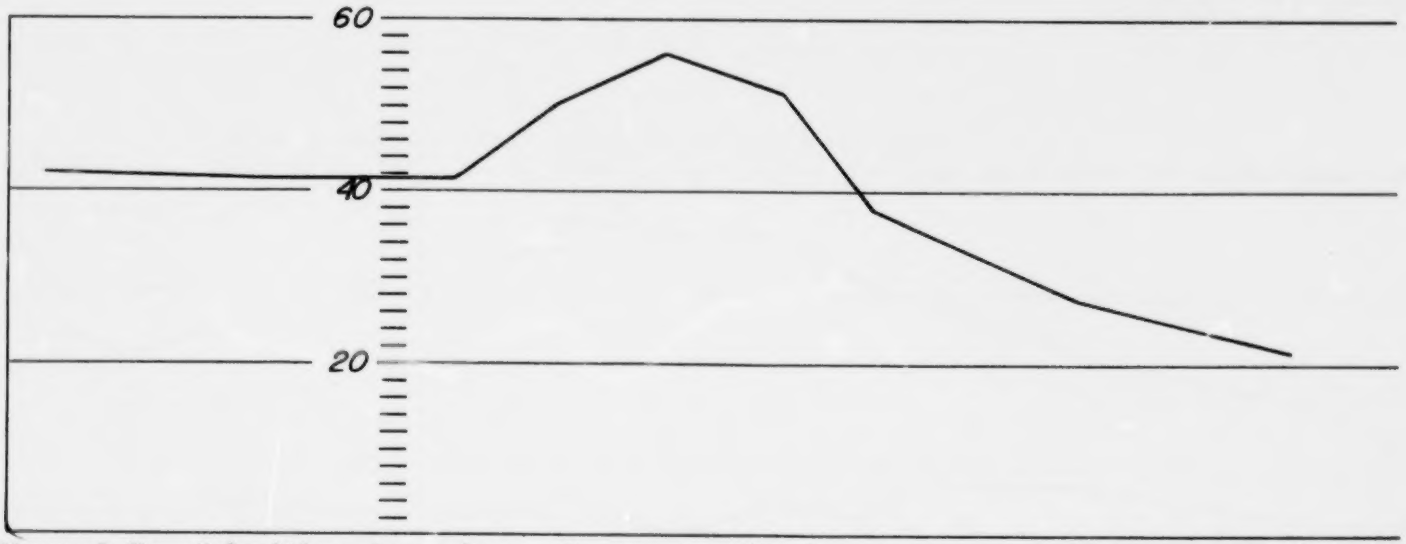


Figure I-4b: Velocities, in cm./sec., at corresponding ice measurement location on above transect.

[redacted]

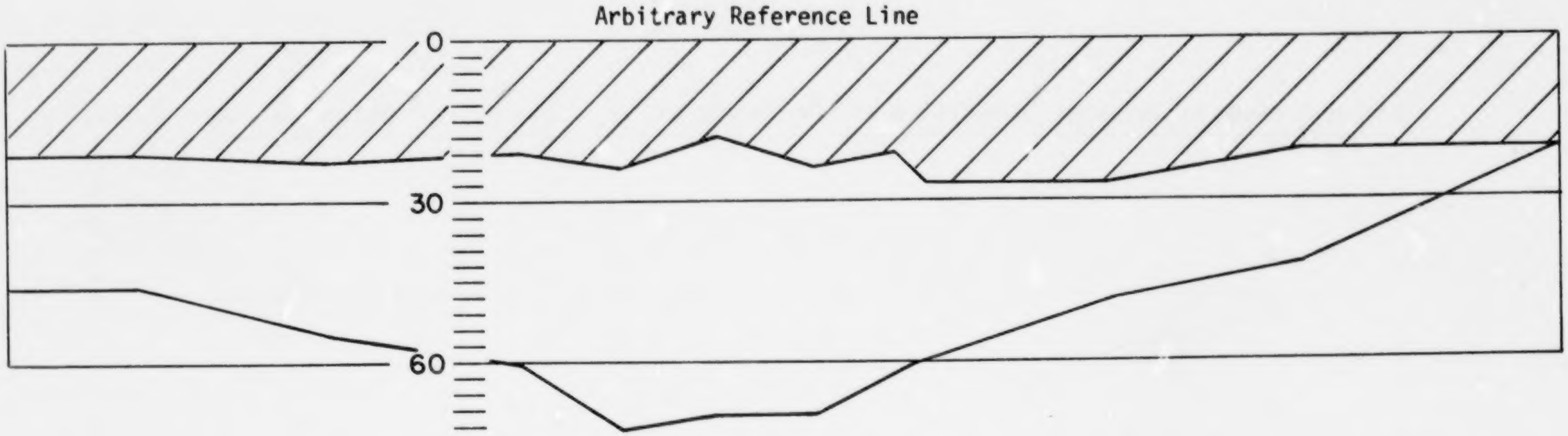


Figure I-5a: Cross-sectional view of channel and surface ice sheet at transect 1, Orcutt Ranch Section, 1/9/76. Vertical scale in cm. below arbitrary datum.

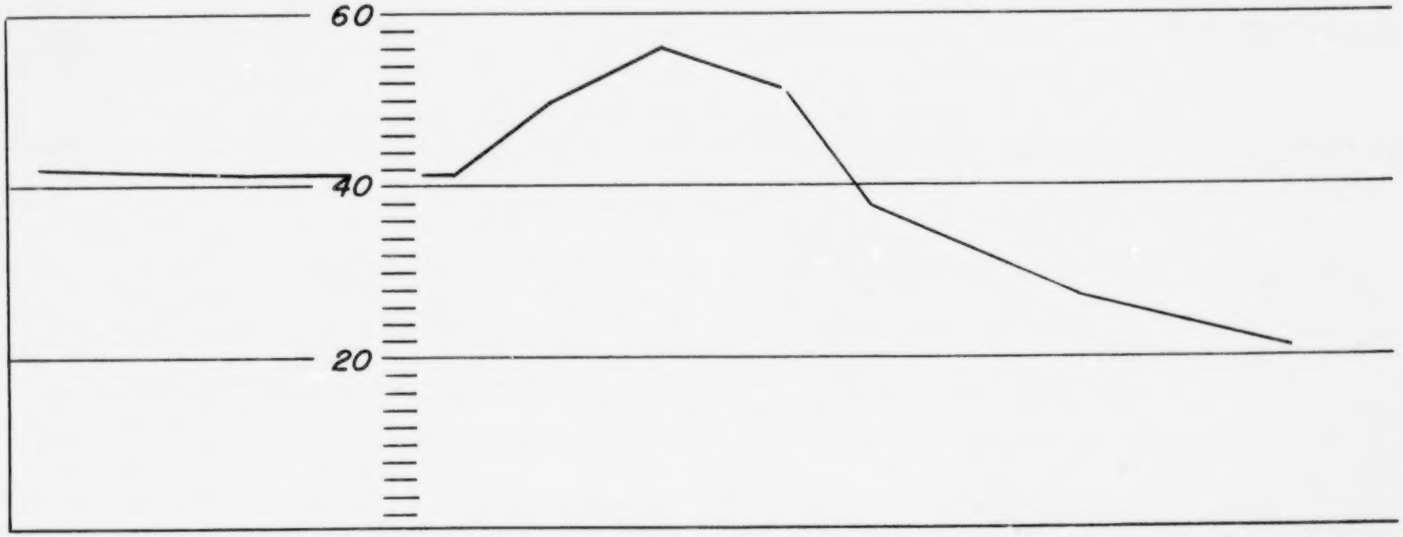


Figure I-5b: Velocities, in cm./sec., at corresponding ice measurement locations on above transect.

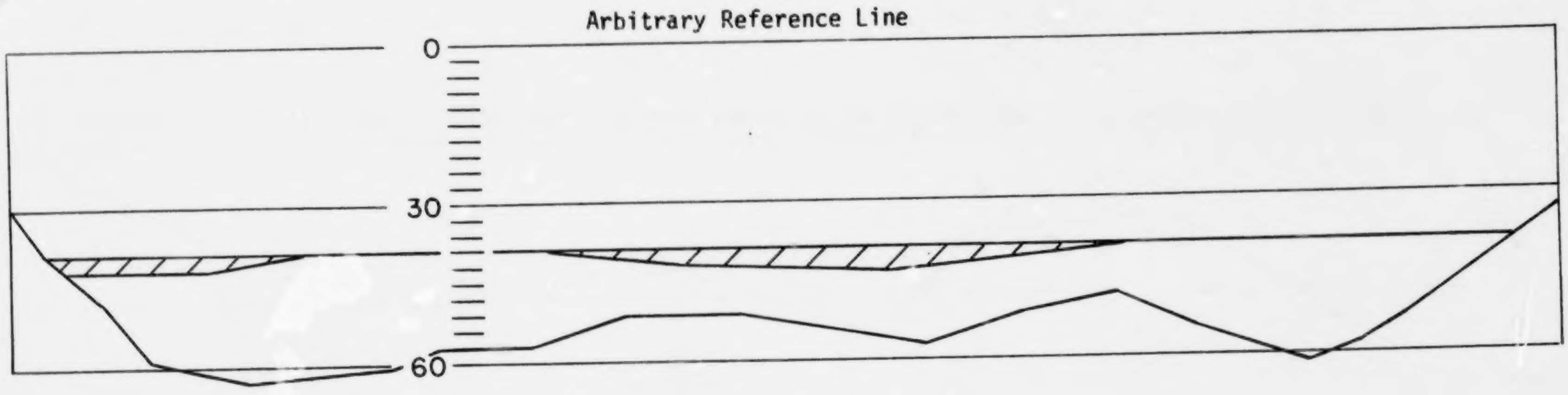


Figure I-6a: Cross-sectional view of channel and surface ice sheet at transect 2, Orcutt Ranch Section, 11/20/75. Vertical scale in cm. below arbitrary datum.

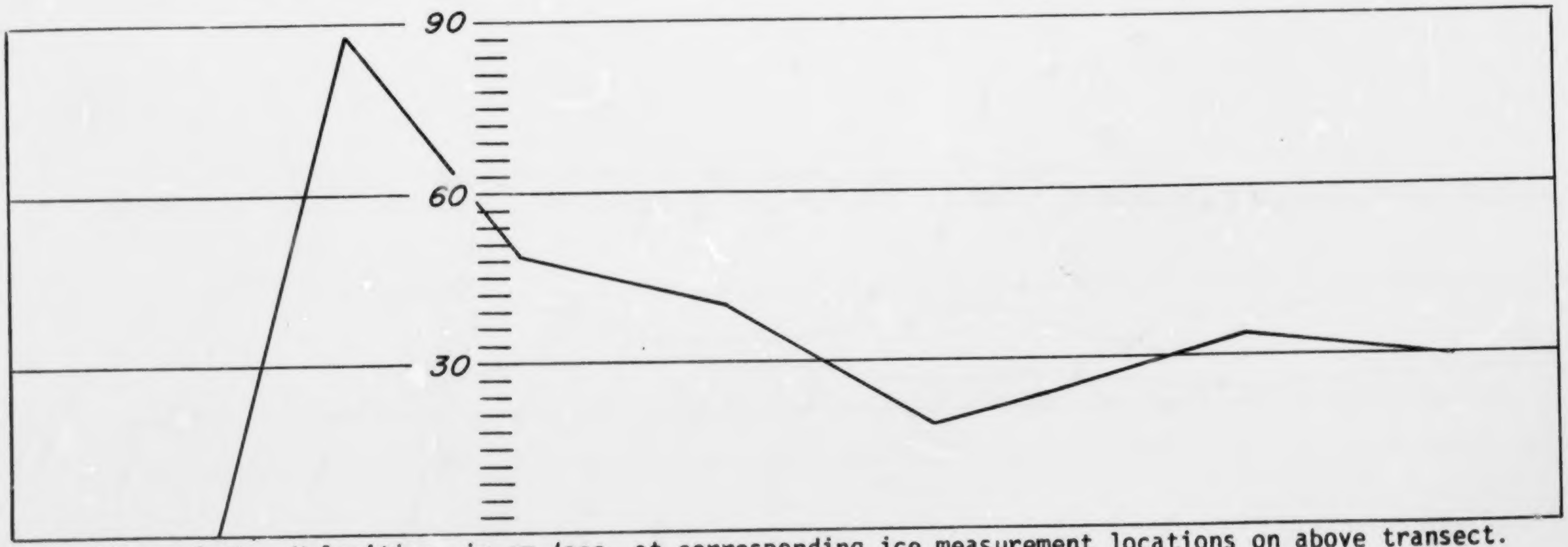


Figure I-6b: Velocities, in cm./sec. at corresponding ice measurement locations on above transect.

[redacted]

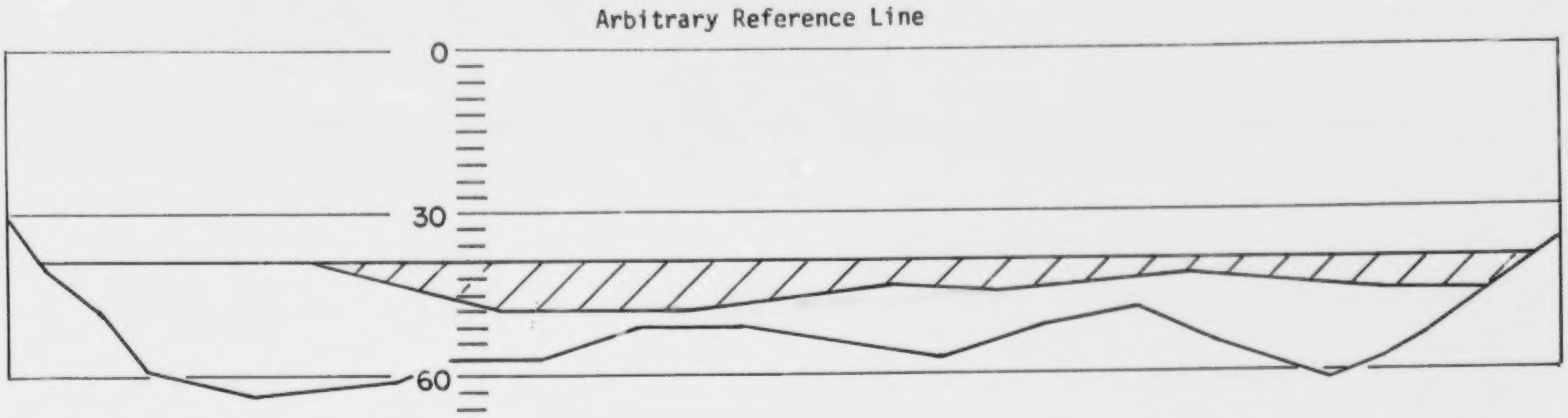


Figure I-7a: Cross-sectional view of channel and surface ice sheet at transect 2, Orcutt Ranch Section, 11/26/75. Vertical scale in cm. below arbitrary datum.

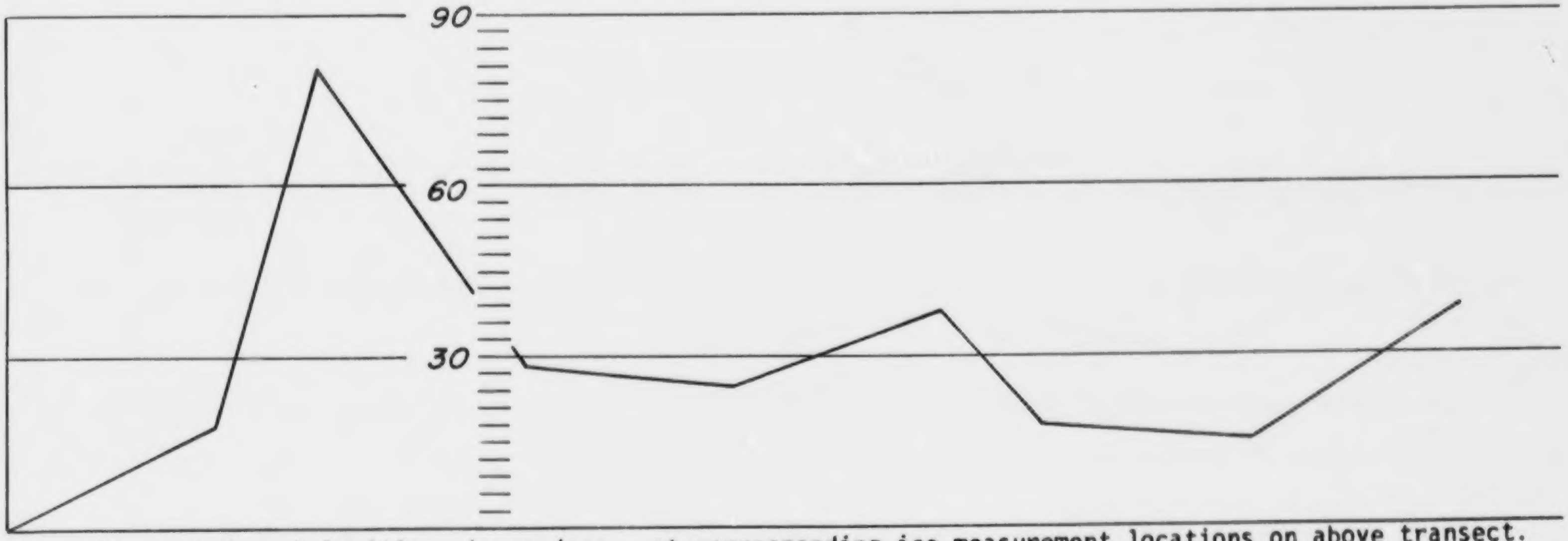


Figure I-7b: Velocities, in cm./sec., at corresponding ice measurement locations on above transect.

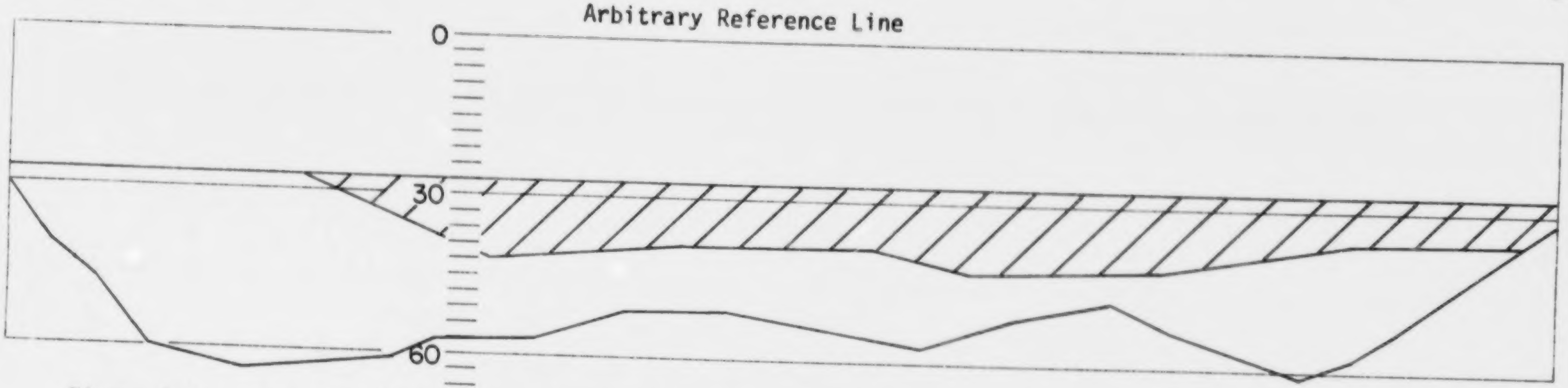


Figure I-8a: Cross-sectional view of channel and surface ice sheet at transect 2, Orcutt Ranch Section, 12/4/75. Vertical scale in cm. below arbitrary datum.

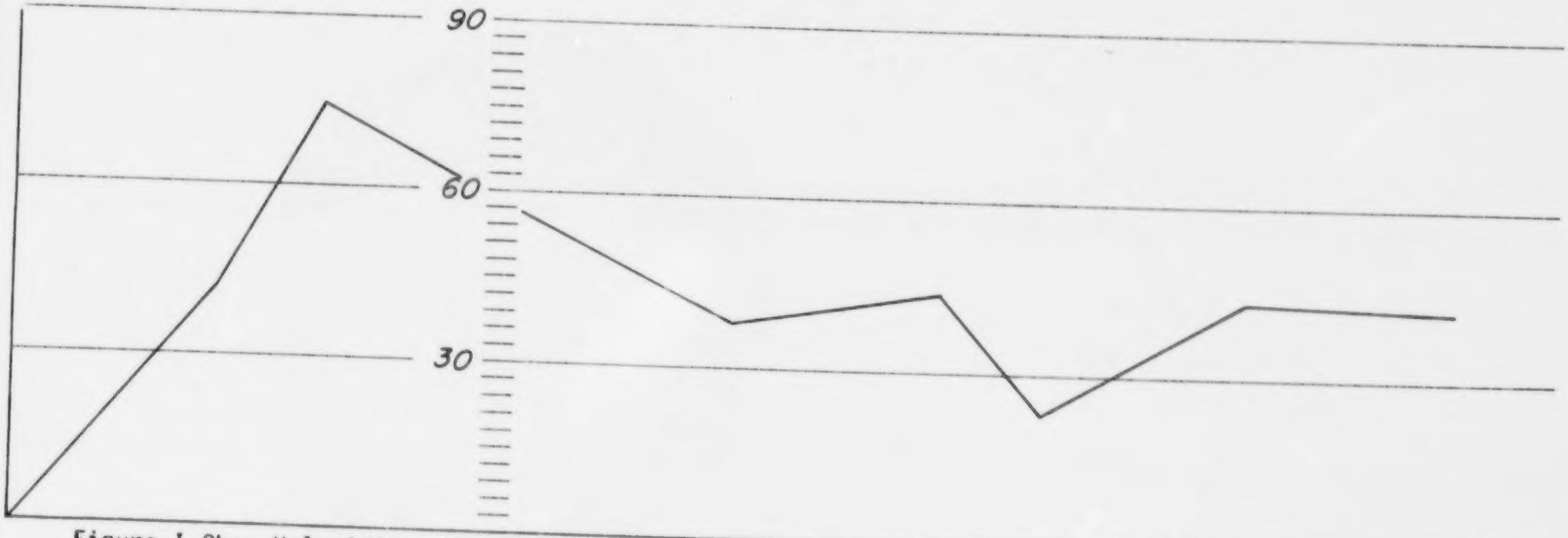


Figure I-8b: Velocities, in cm./sec., at corresponding ice measurement locations on above transect.

[redacted]

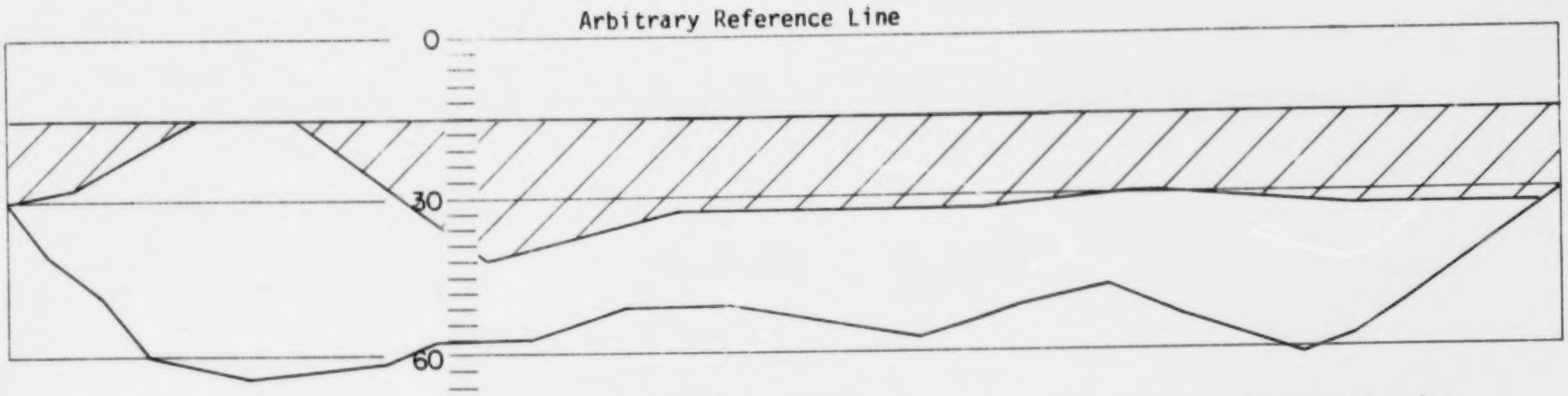


Figure I-9a: Cross-sectional view of channel and surface ice sheet at transect 2, Orcutt Ranch Section, 12/23/75. Vertical scale in cm. below arbitrary datum.

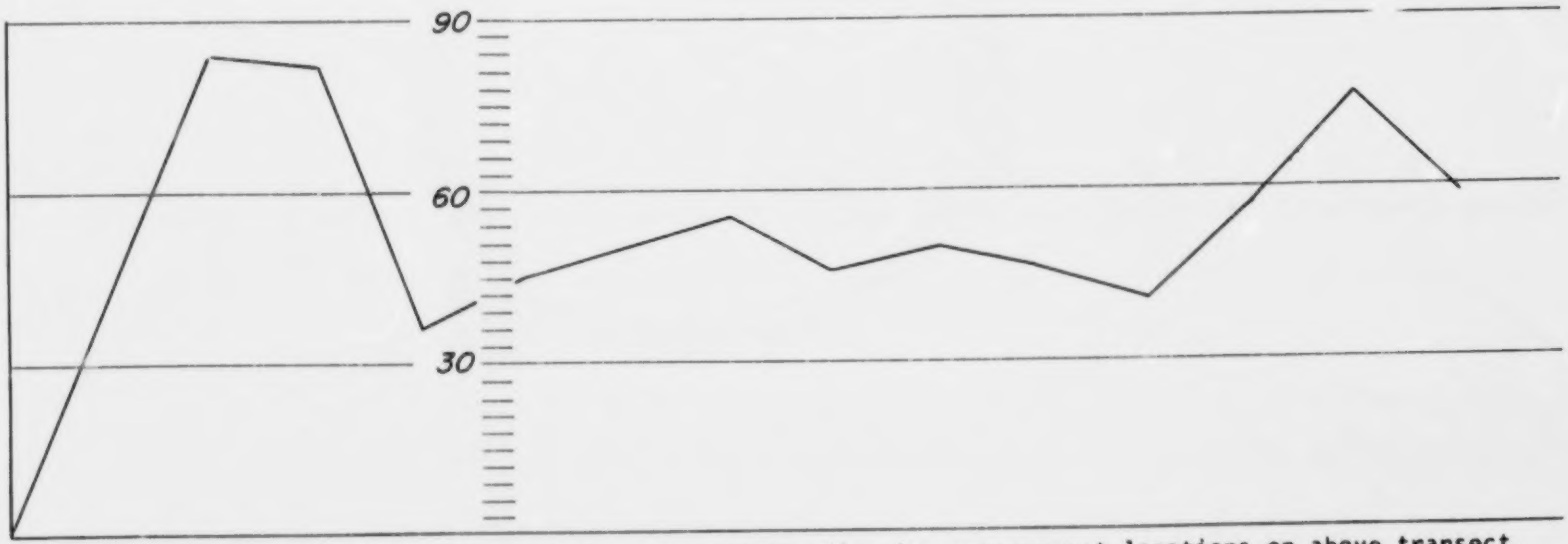


Figure I-9b: Velocities, in cm./sec., at corresponding ice measurement locations on above transect.

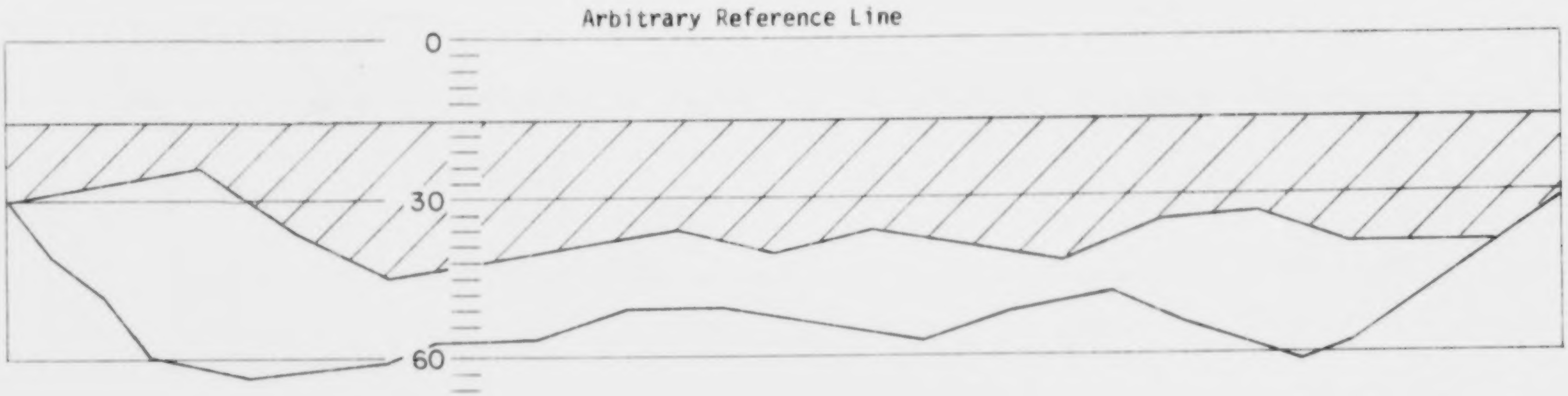


Figure I-10a: Cross-sectional view of channel and surface ice sheet at transect 2, Orcutt Ranch Section, 1/9/76. Vertical scale in cm. below arbitrary datum.

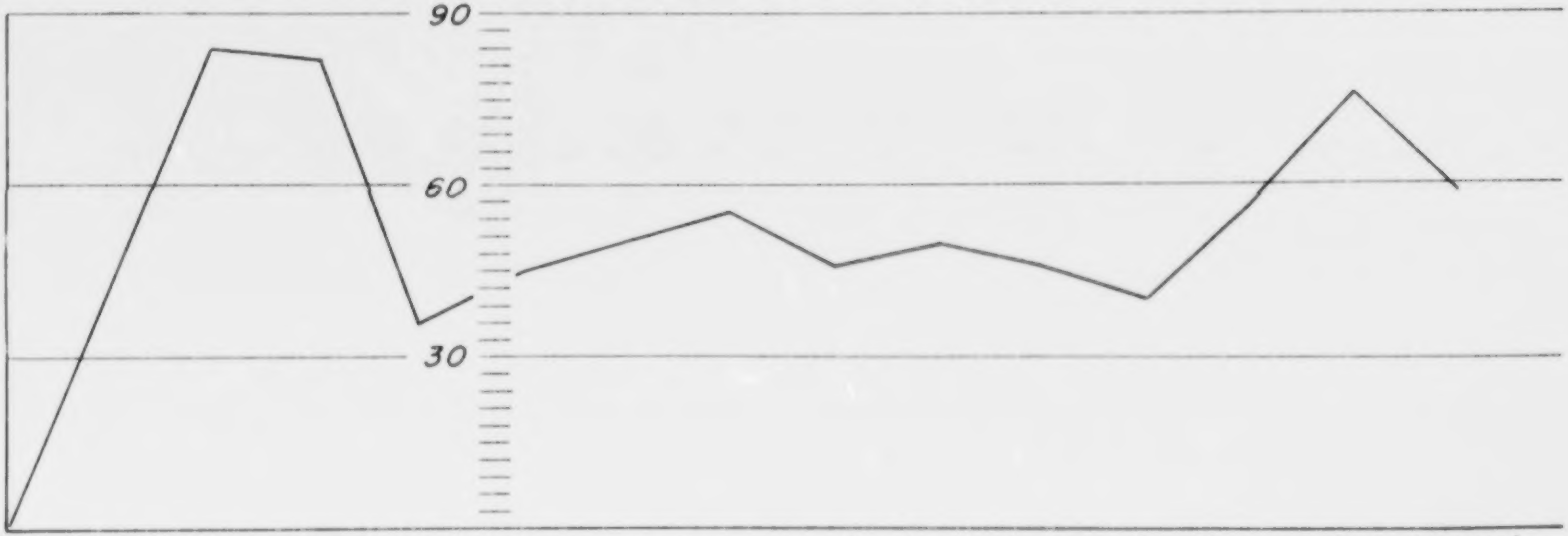


Figure I-10b: Velocities, in cm./sec., at corresponding ice measurement locations on above transect.

[redacted]

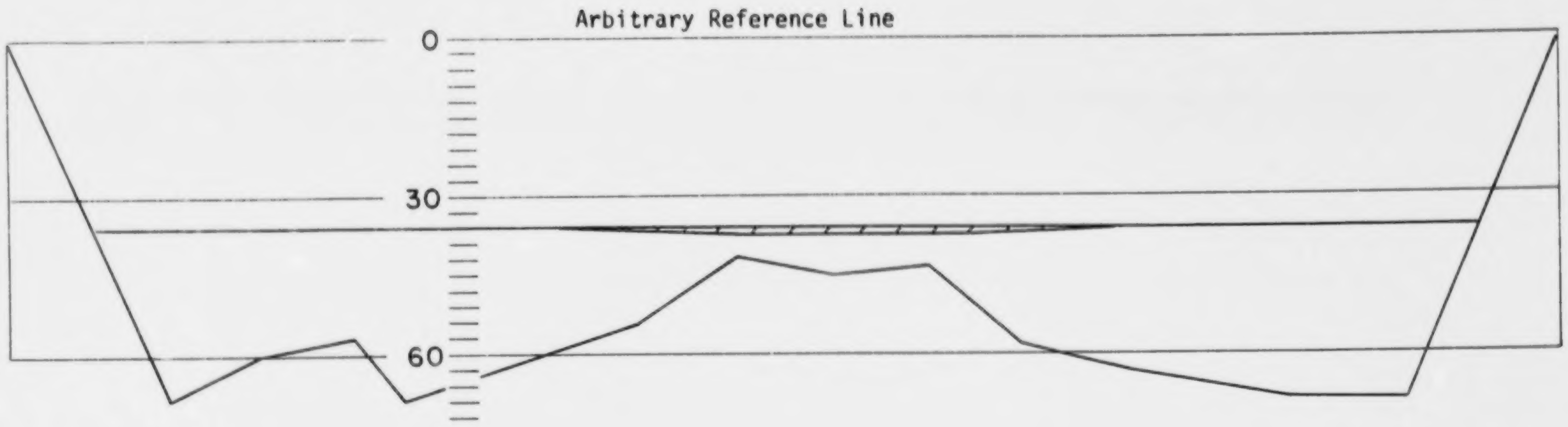


Figure I-11a: Cross-sectional view of channel and surface ice sheet at transect 3, Orcutt Ranch Section, 11/20/75. Vertical scale in cm. below arbitrary datum.

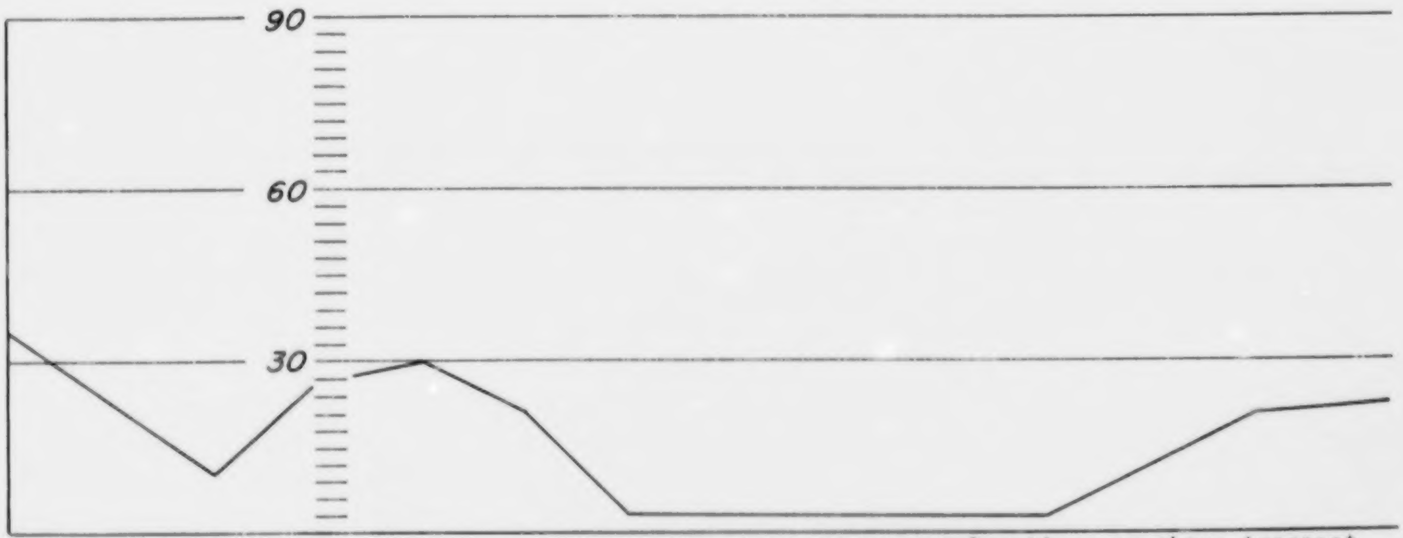


Figure I-11b: Velocities, in cm./sec., at corresponding ice measurement locations on above transect.

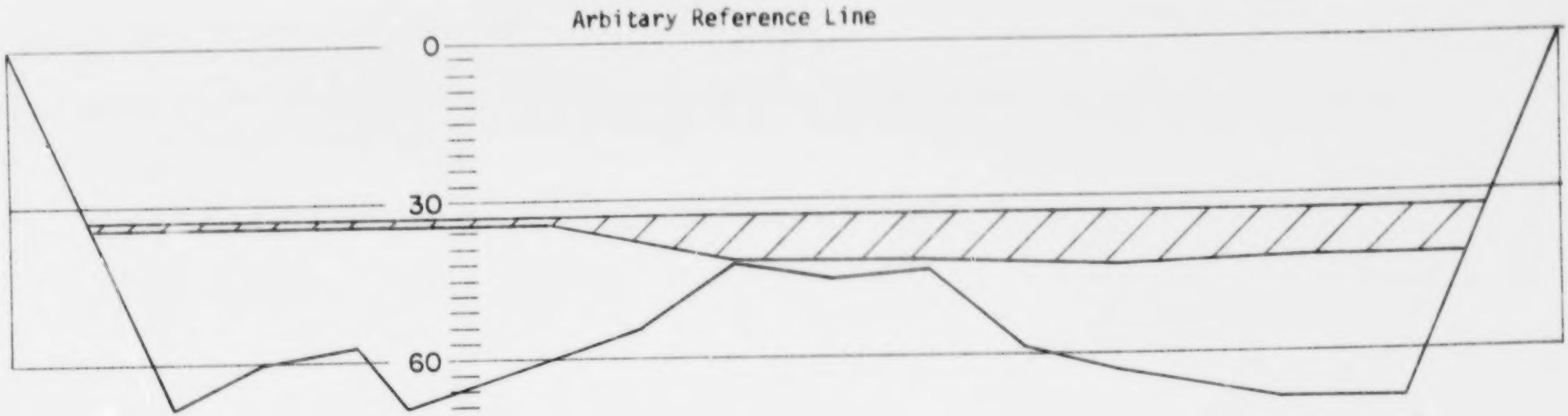


Figure I-12a: Cross-sectional view of channel and surface ice sheet at transect 3, Orcutt Ranch Section, 11/26/75. Vertical scale in cm. below arbitrary datum.

[redacted]

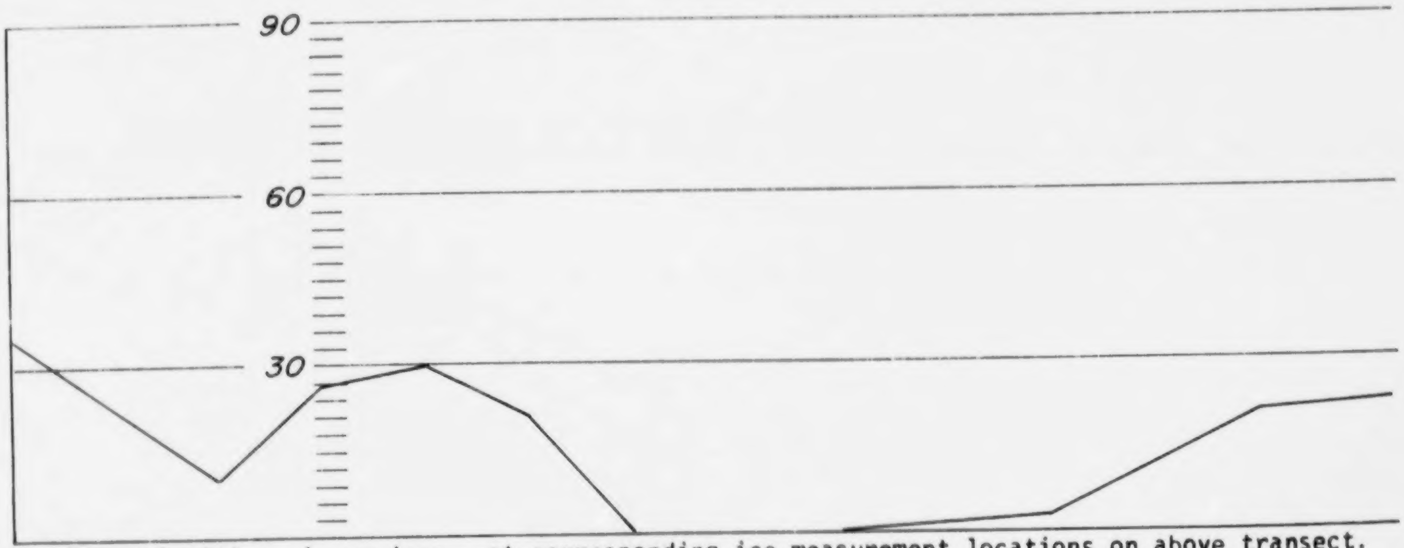


Figure I-12b: Velocities, in cm./sec., at corresponding ice measurement locations on above transect.

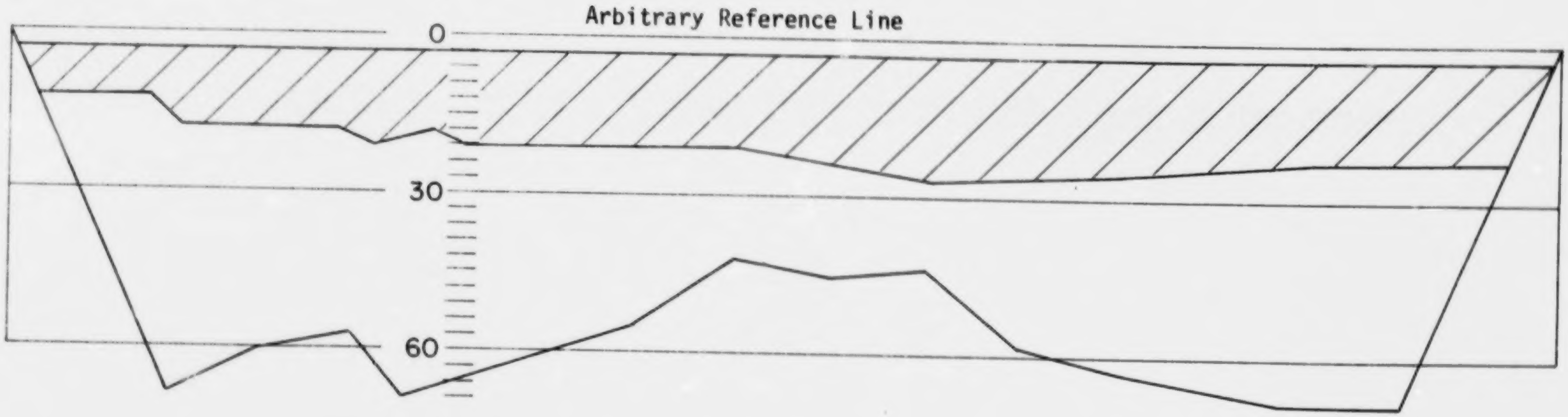


Figure I-13a: Cross-sectional view of channel and surface ice sheet at transect 3, Orcutt Ranch Section, 12/10/75. Vertical scale in cm. below arbitrary datum.

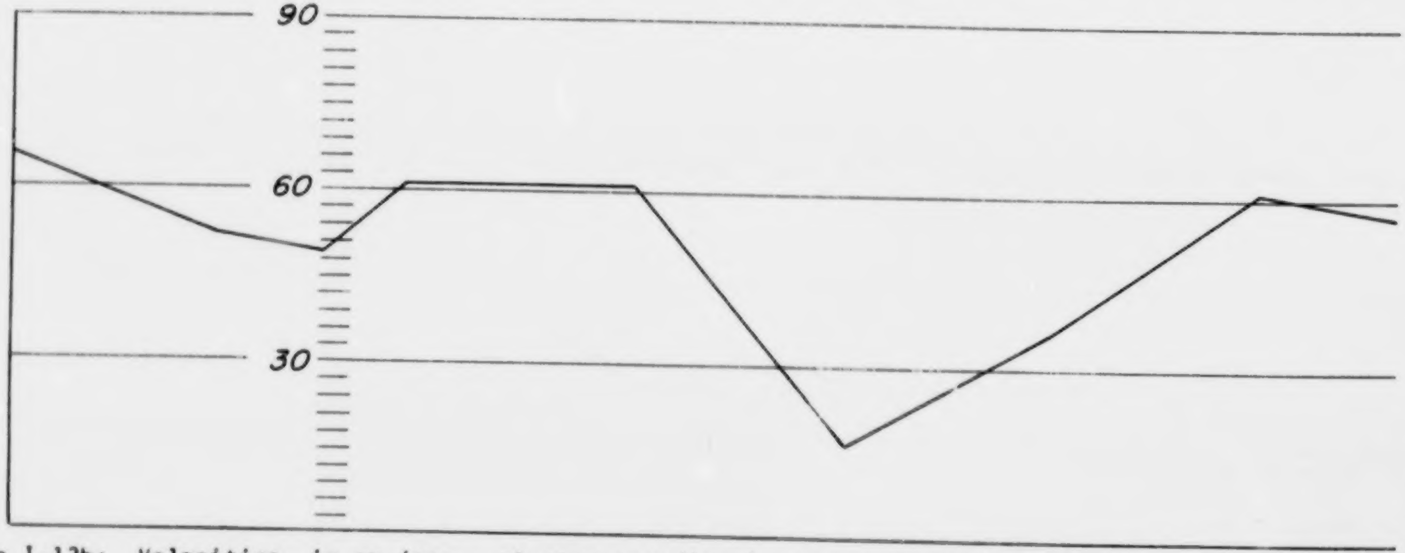


Figure I-13b: Velocities, in cm./sec., at corresponding ice measurement locations on above transect.

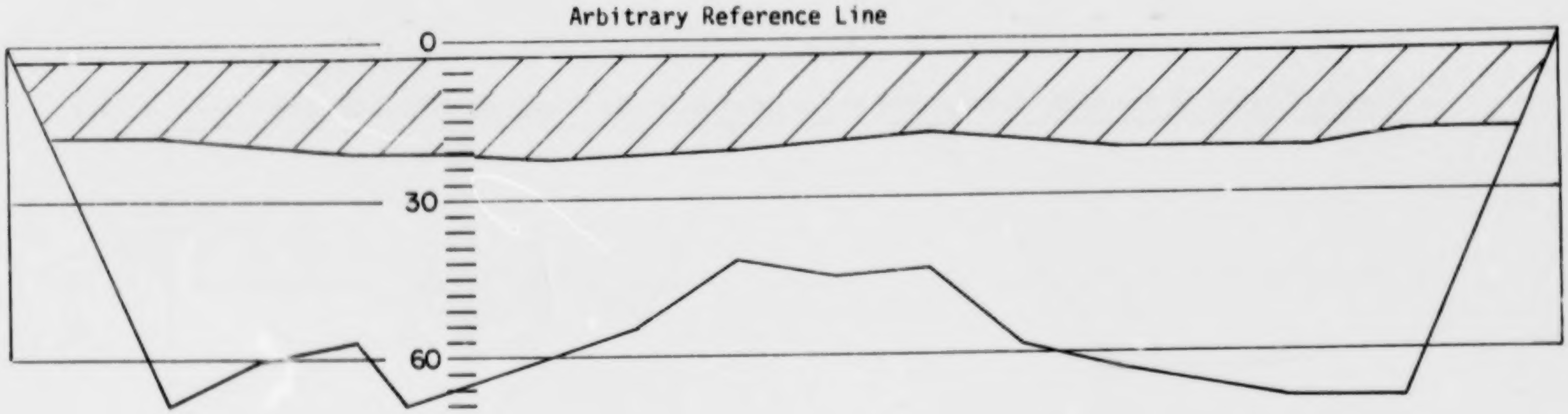


Figure I-14a: Cross-sectional view of channel and surface ice sheet at transect 3, Orcutt Ranch Section, 12/23/75. Vertical scale in cm. below arbitrary datum.

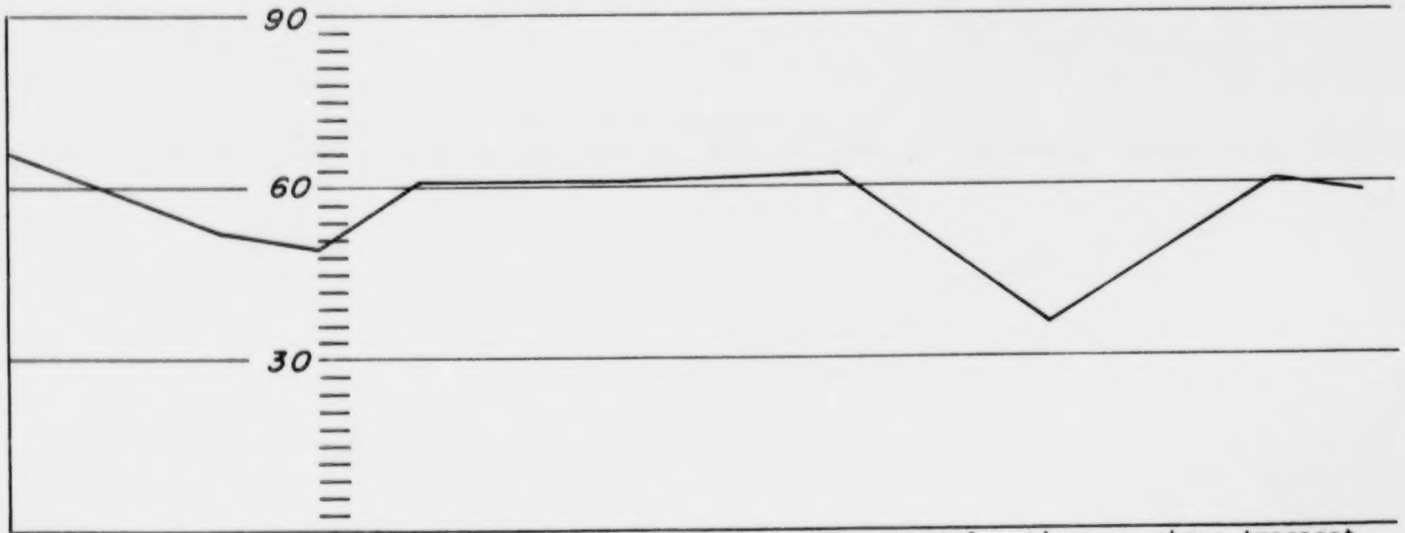


Figure I-14b: Velocities, in cm./sec., at corresponding ice measurement locations on above transect.

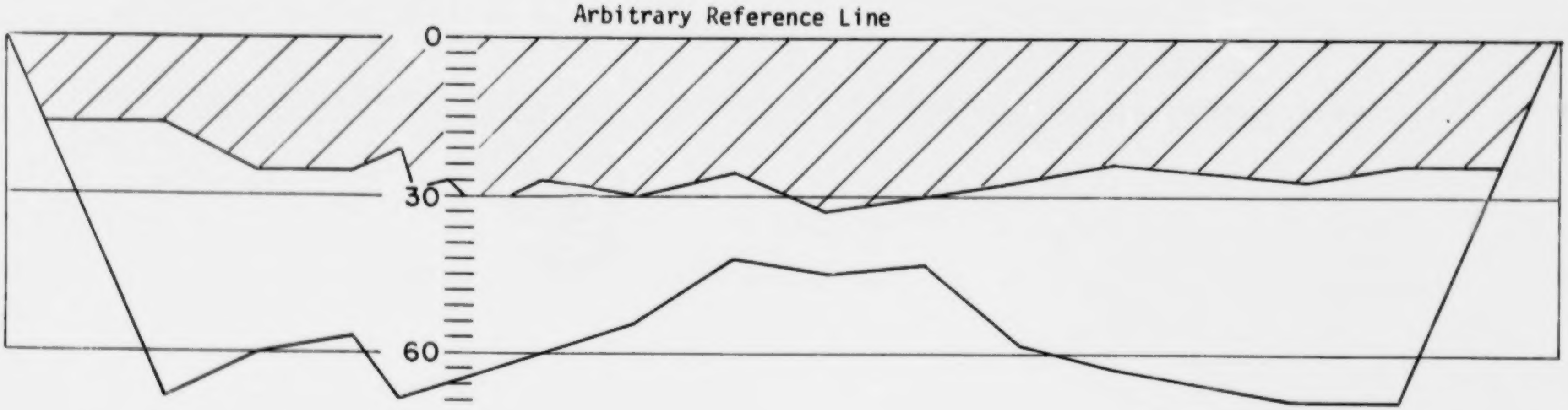


Figure I-15a: Cross-sectional view of channel and surface ice sheet at transect 3, Orcutt Ranch Section, 1/9/76. Vertical scale in cm. below arbitrary datum.

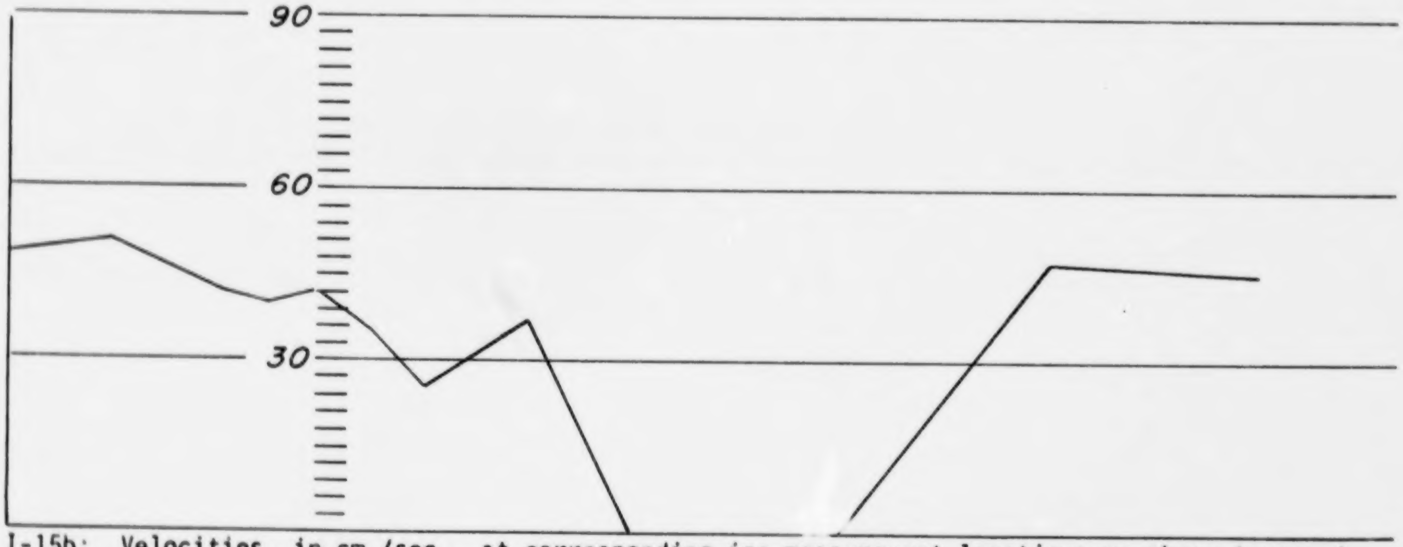


Figure I-15b: Velocities, in cm./sec., at corresponding ice measurement locations on above transect.

APPENDIX J

VEGETATION MAPS OF TONGUE RIVER FLOODPLAIN

LEGEND

■ 100% Cover

▓ 90% Cover

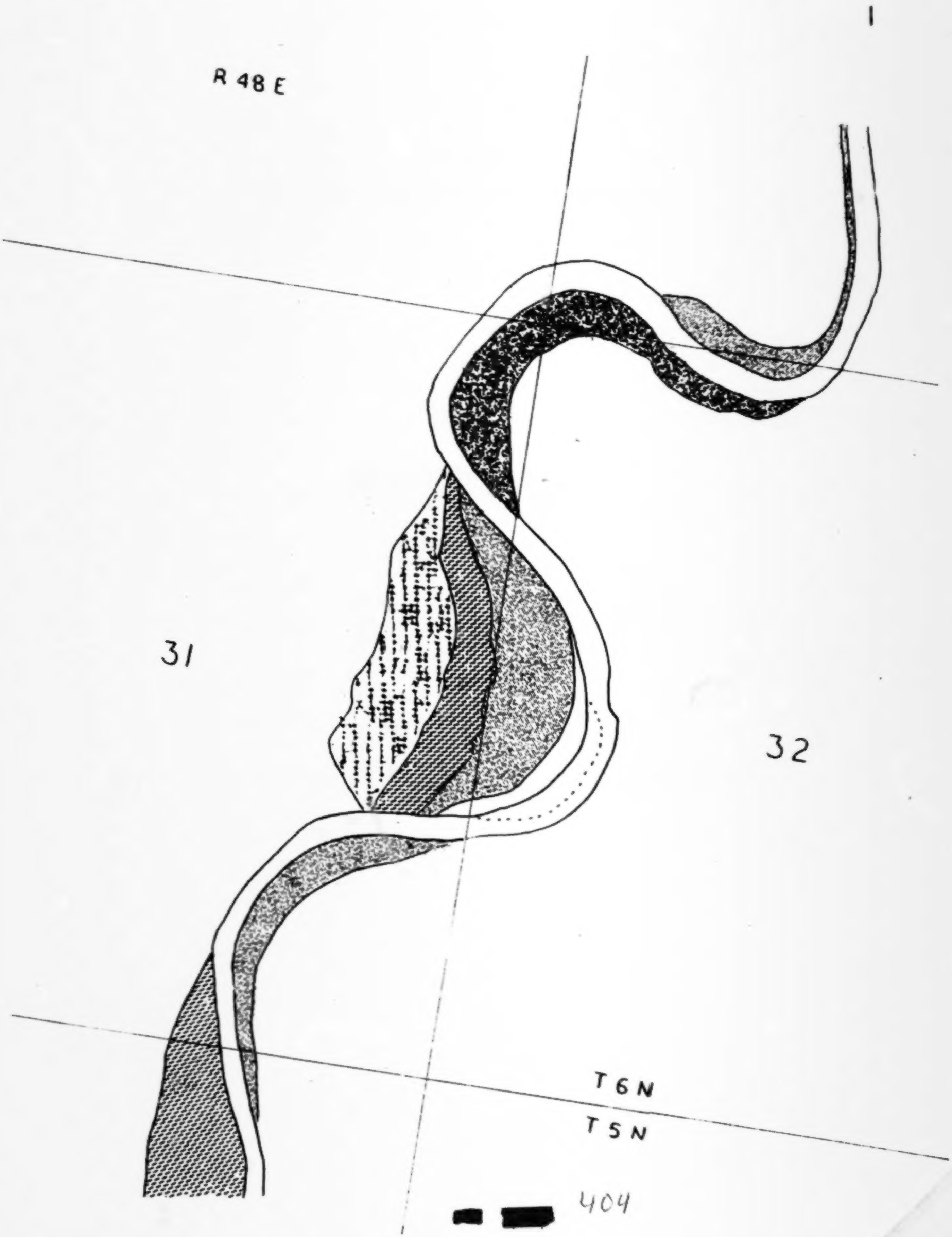
▒ 75% Cover

▨ 50% Cover

░ 25% Cover

▥ 10% Cover

□ 0% Cover



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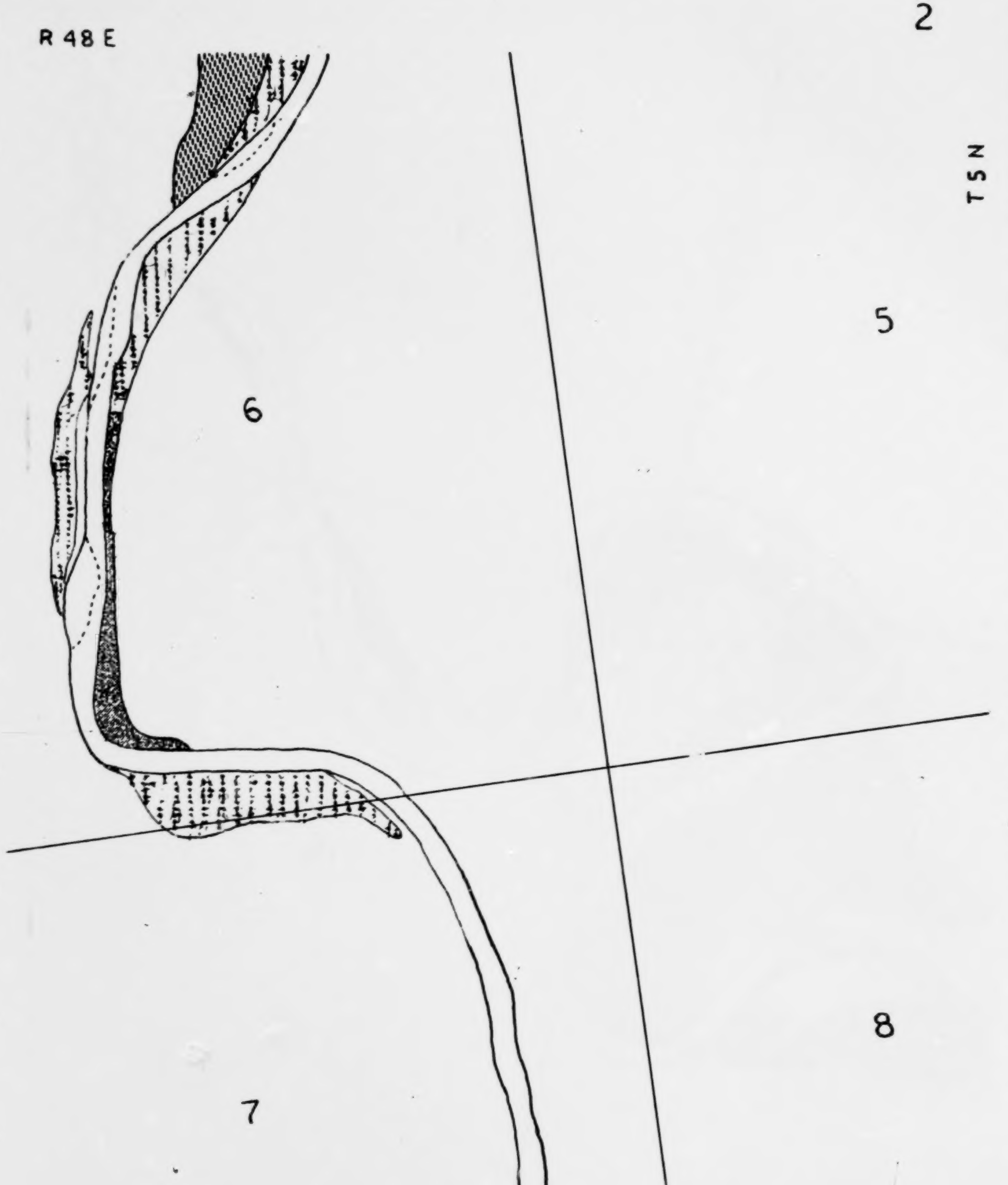
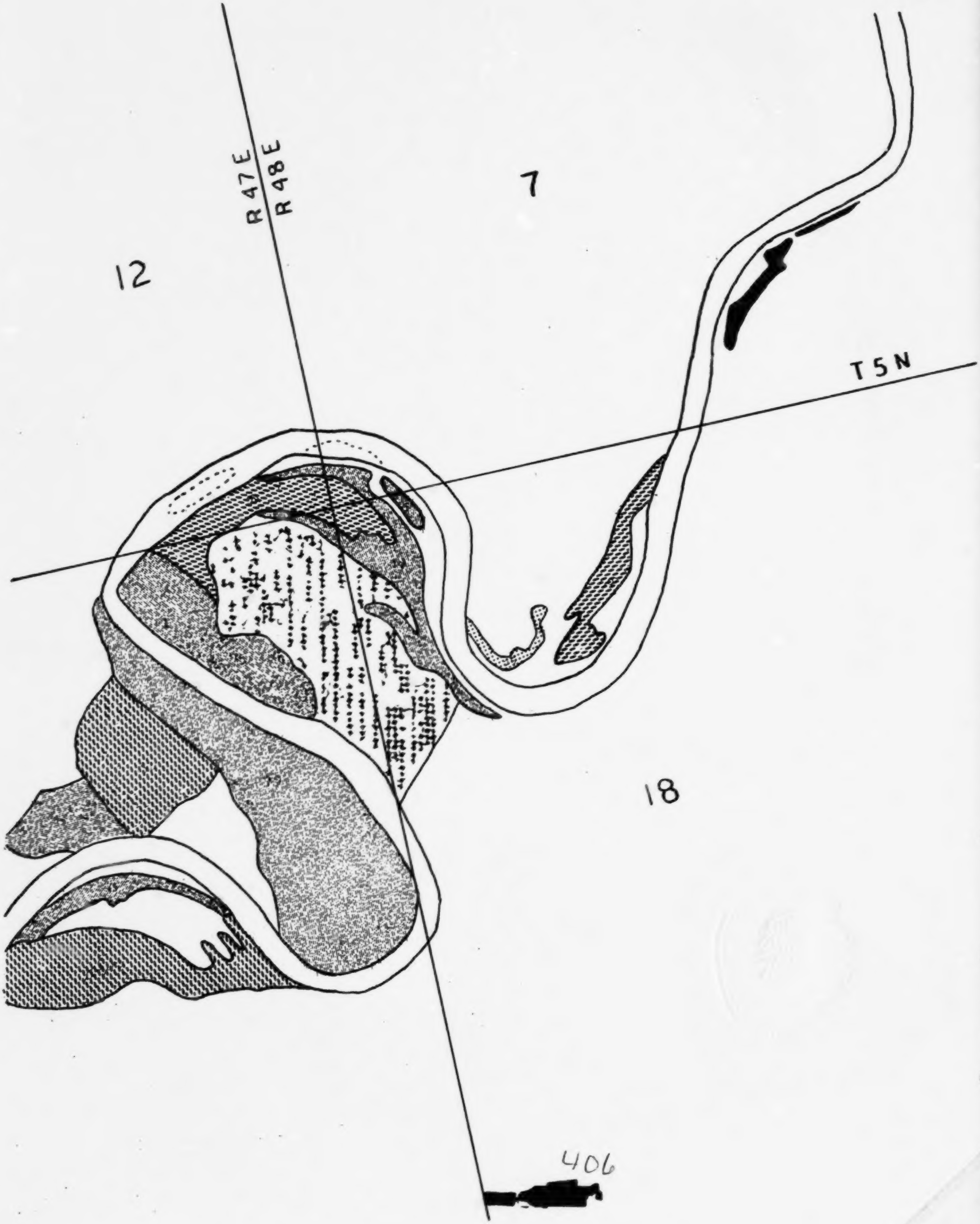

R 48 E
2
T 5 N
5
6
7
8

3



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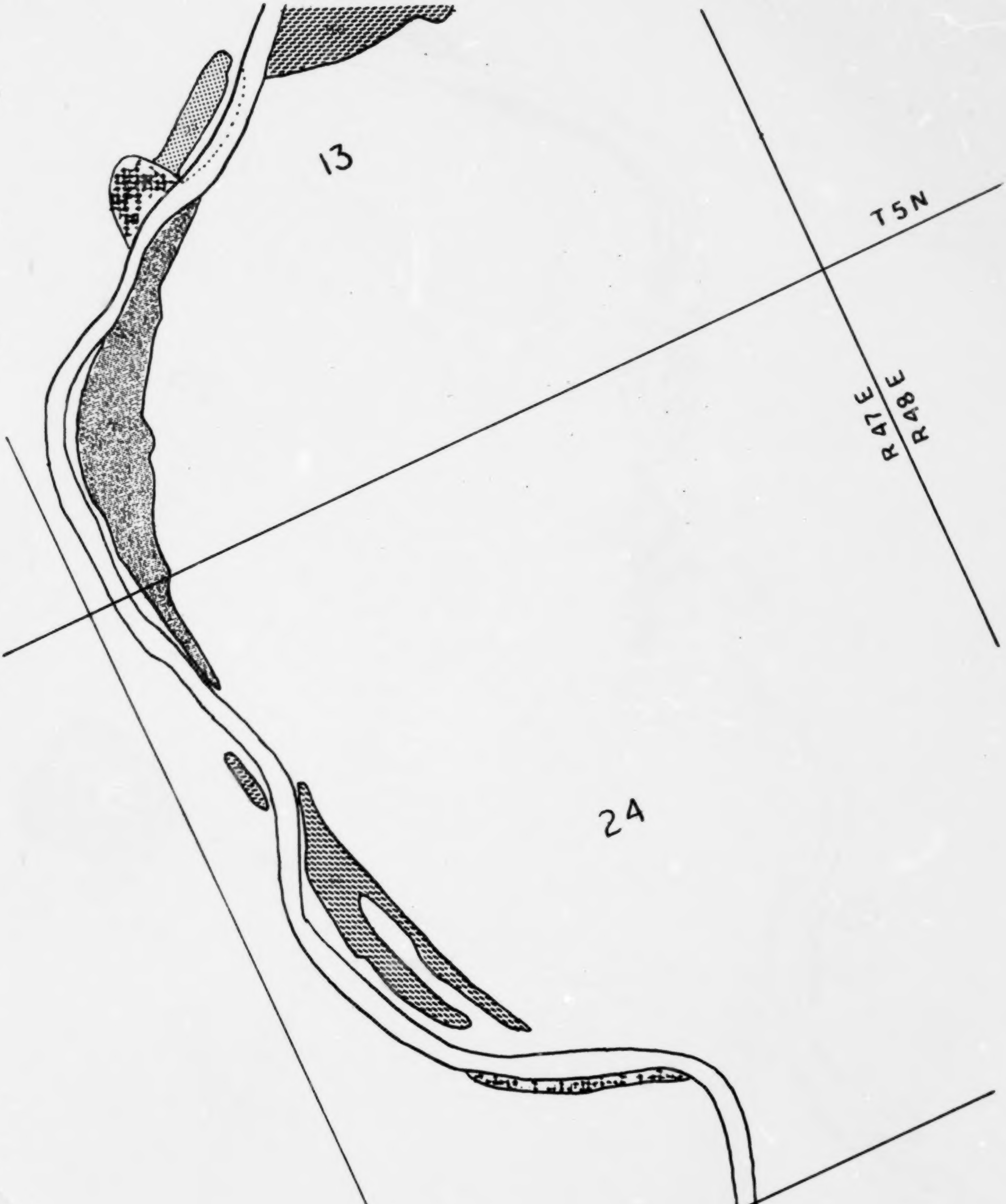

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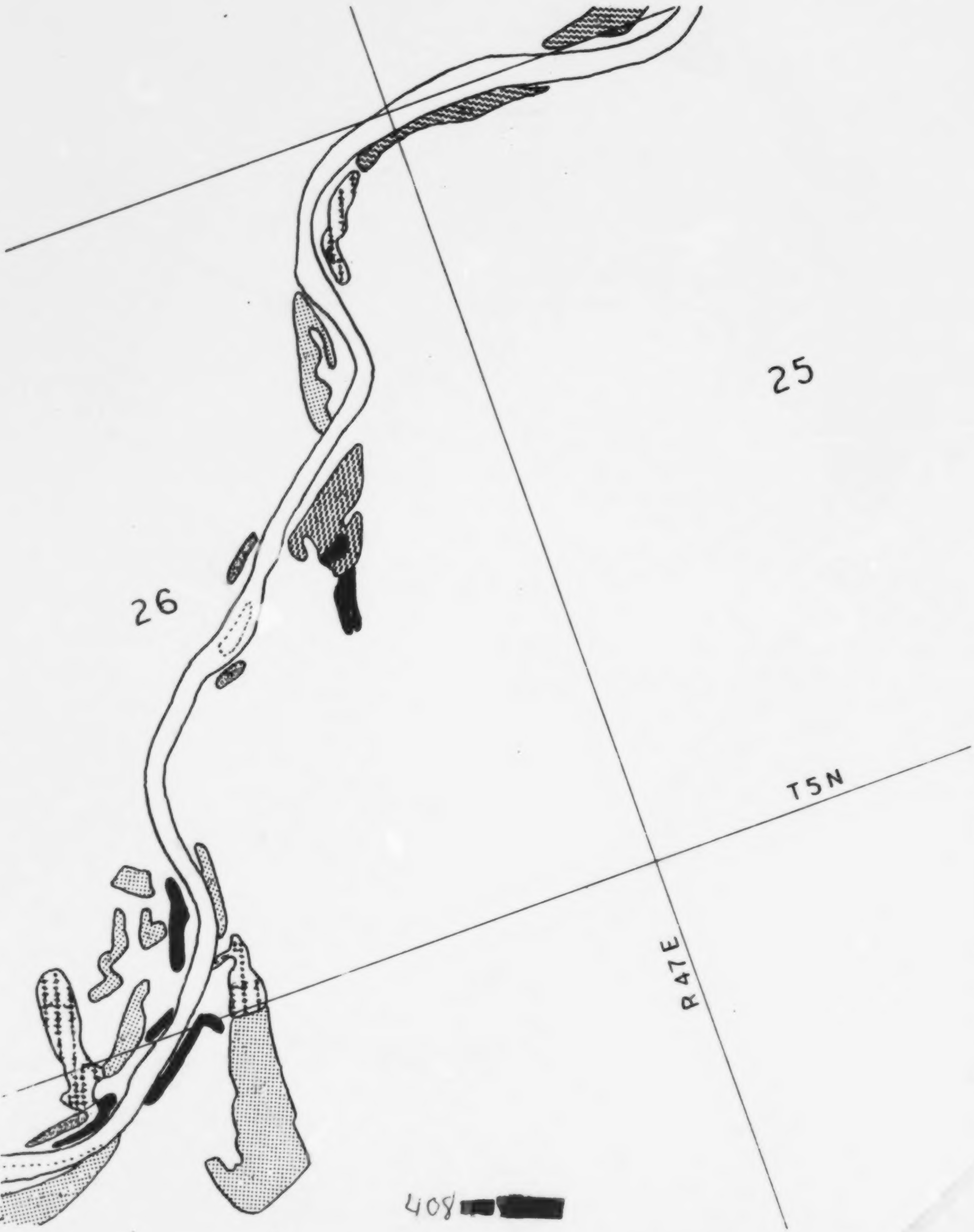

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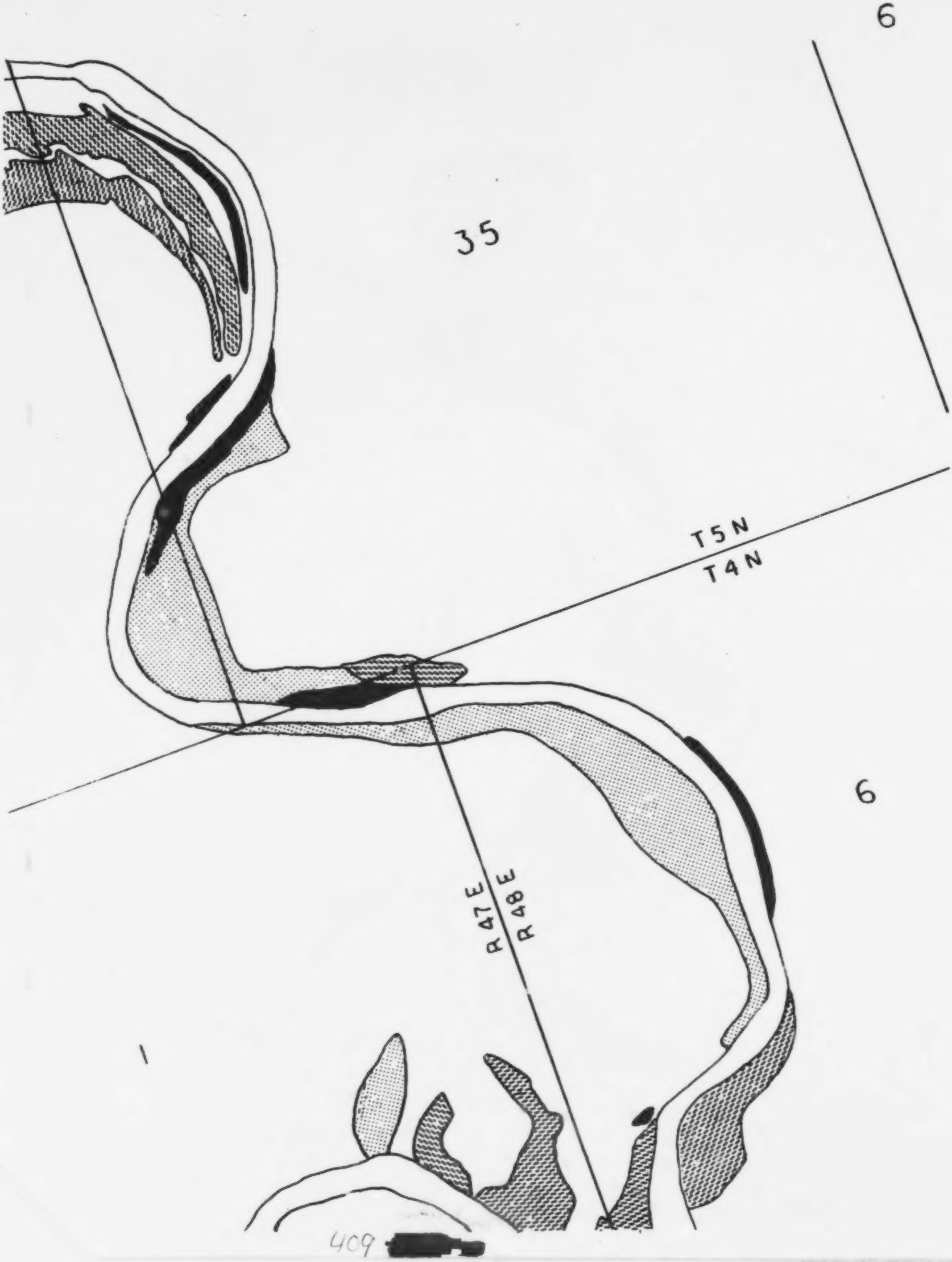

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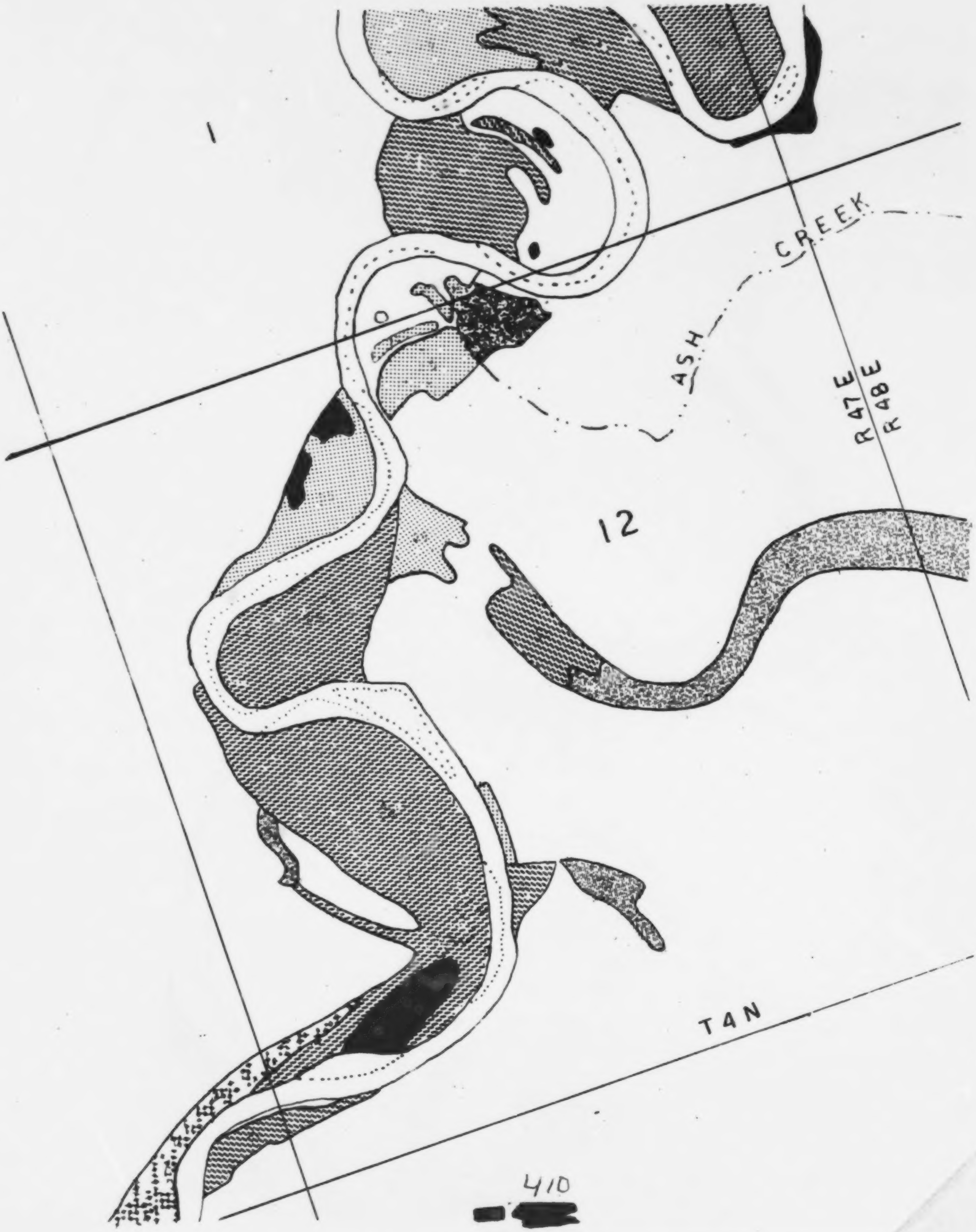

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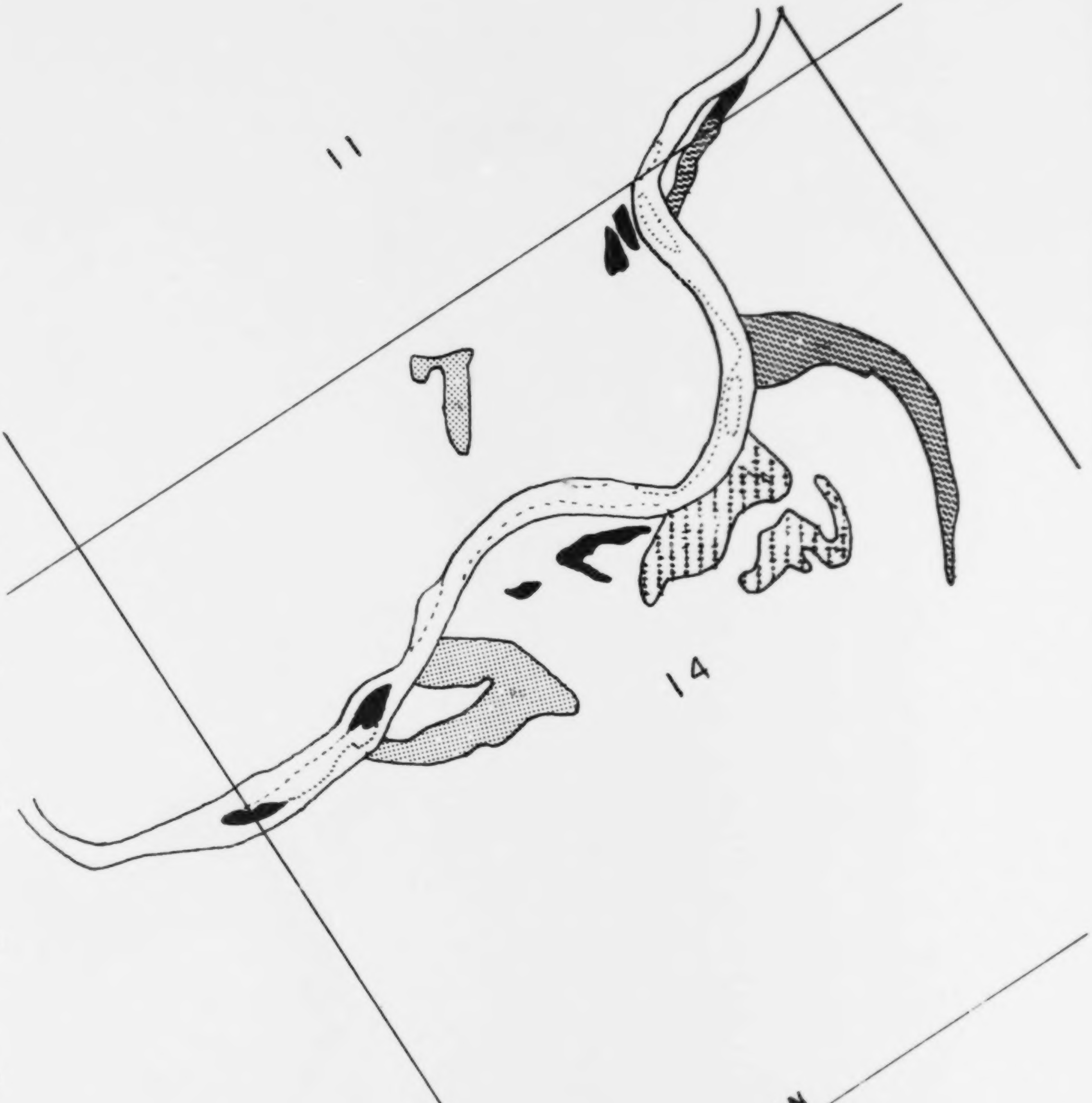
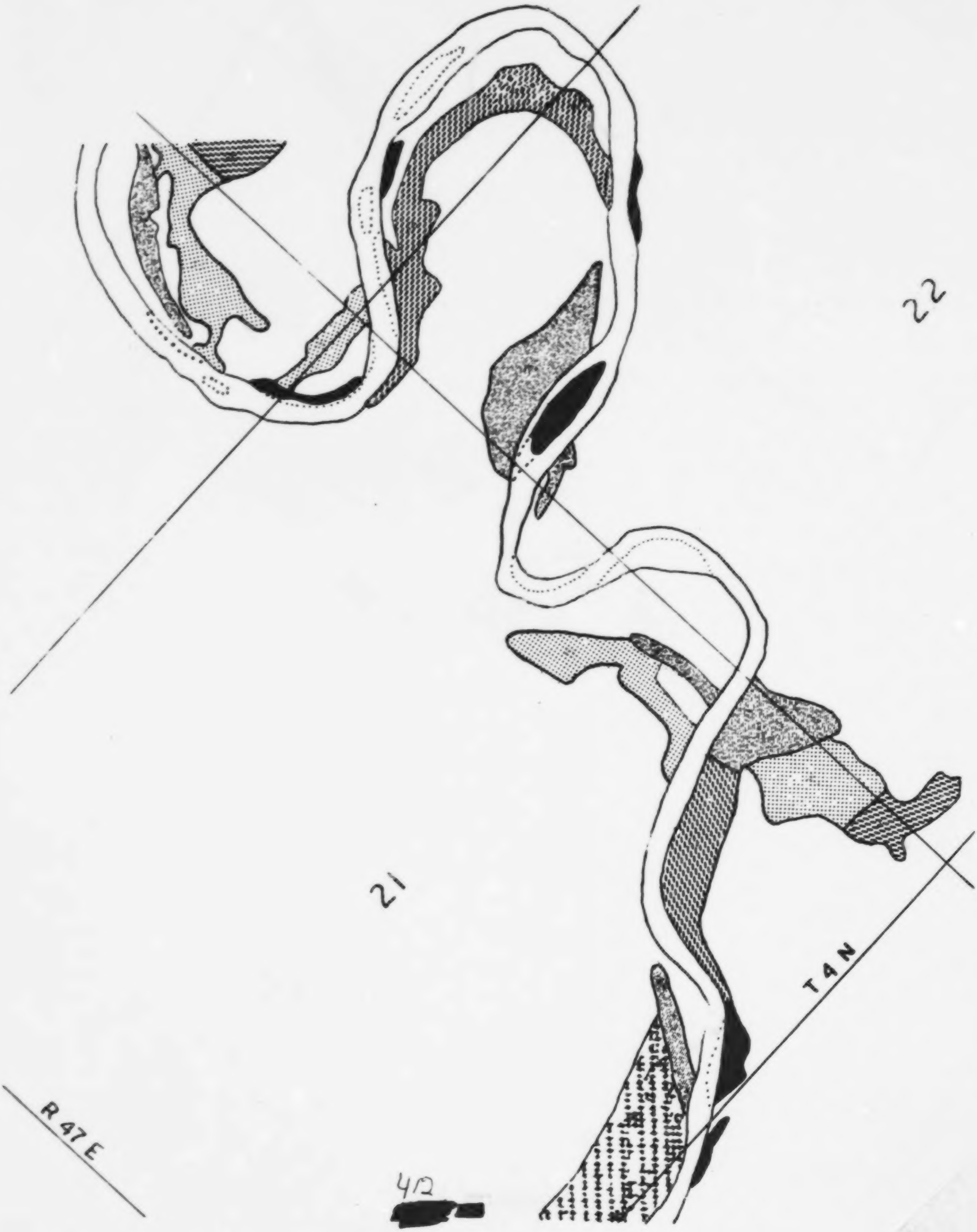

11
14
R47E
T4N



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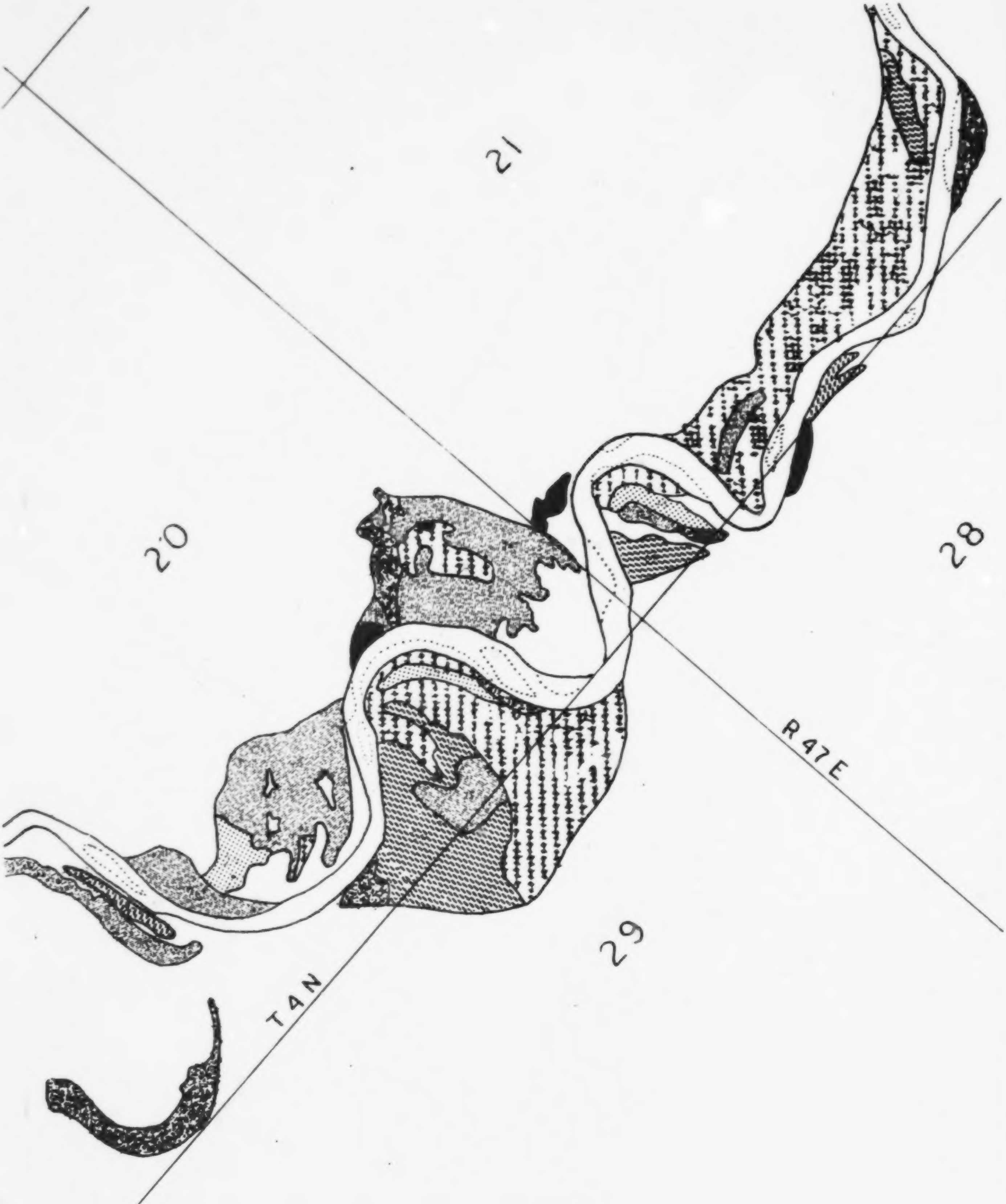

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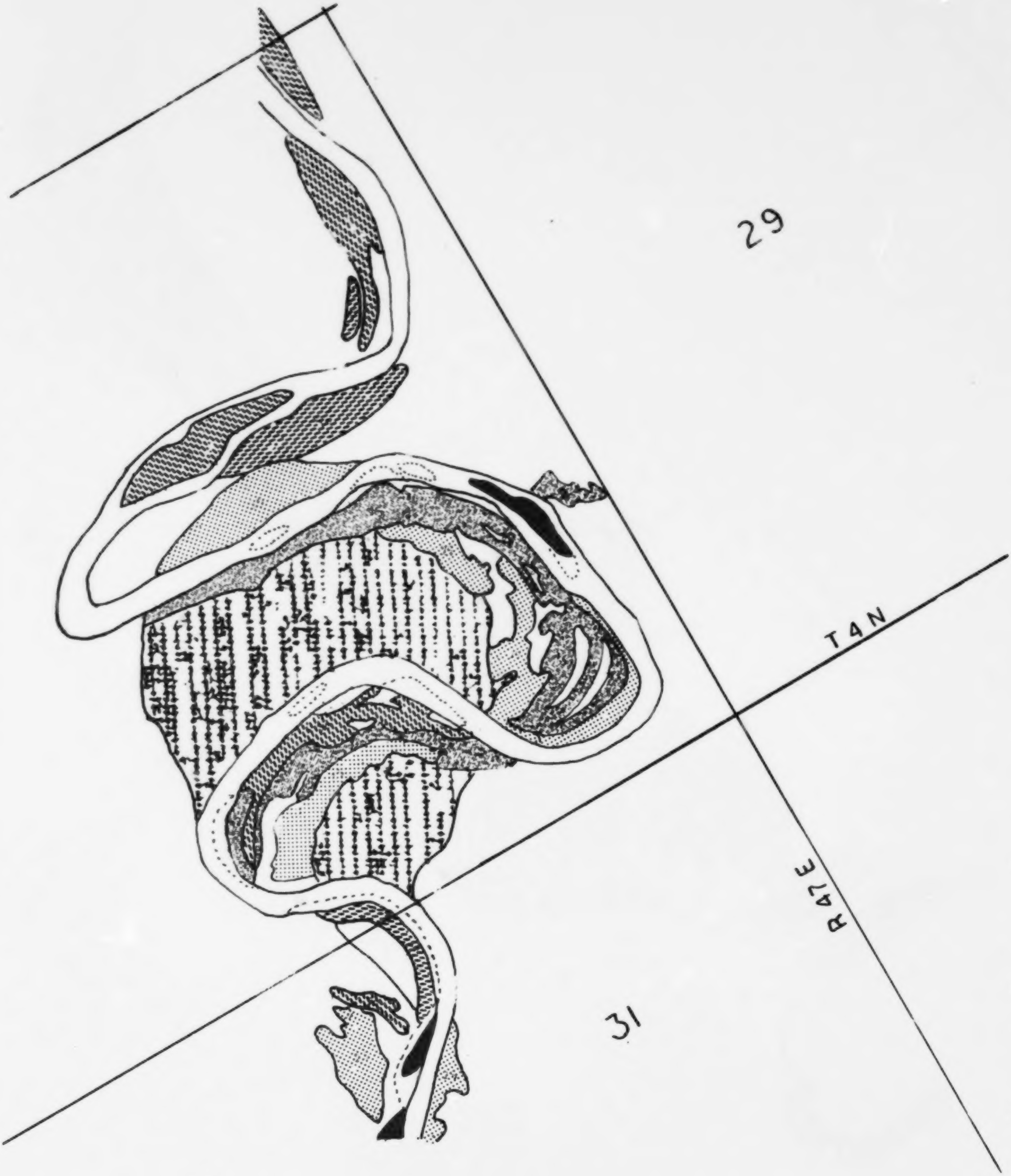

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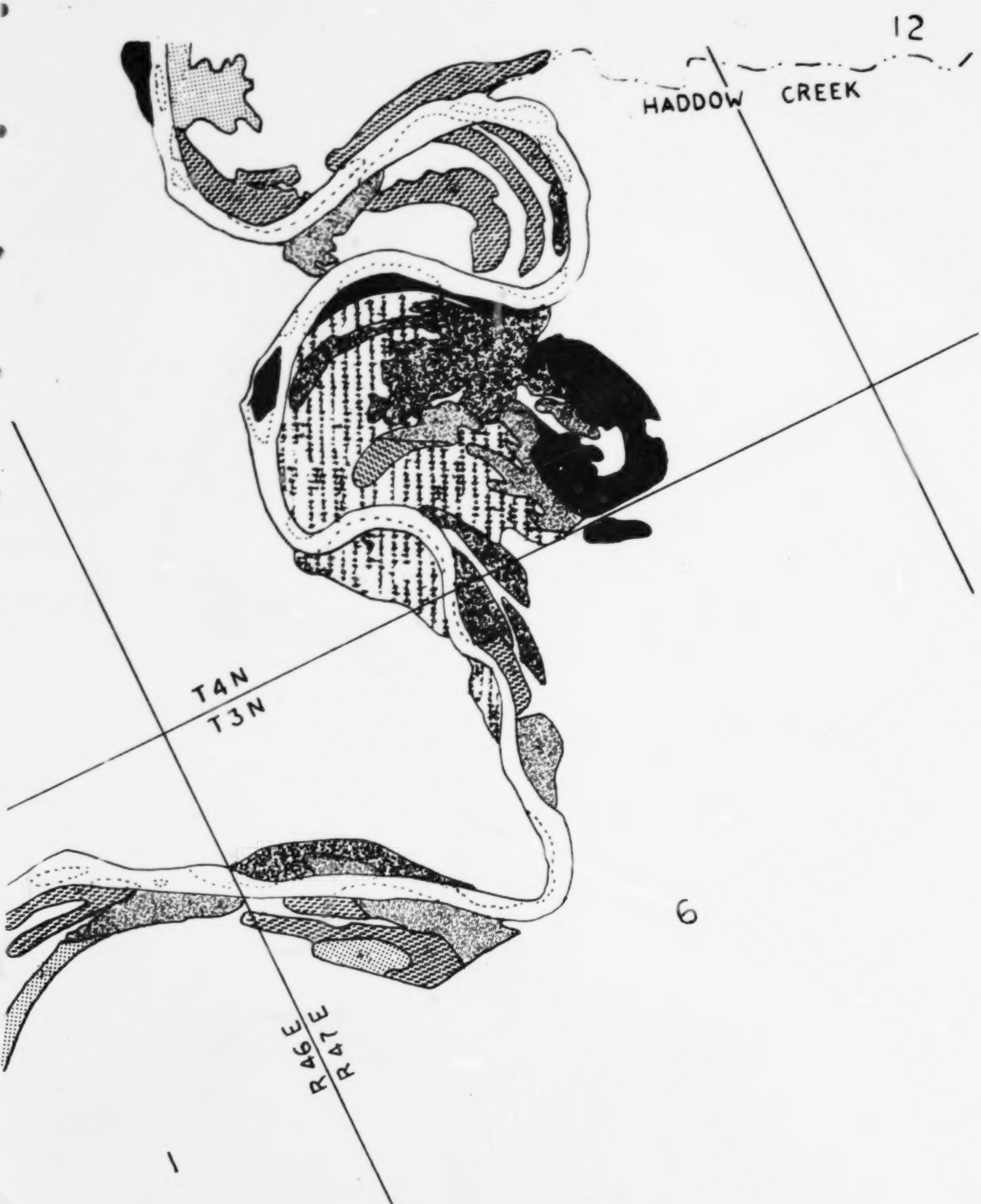

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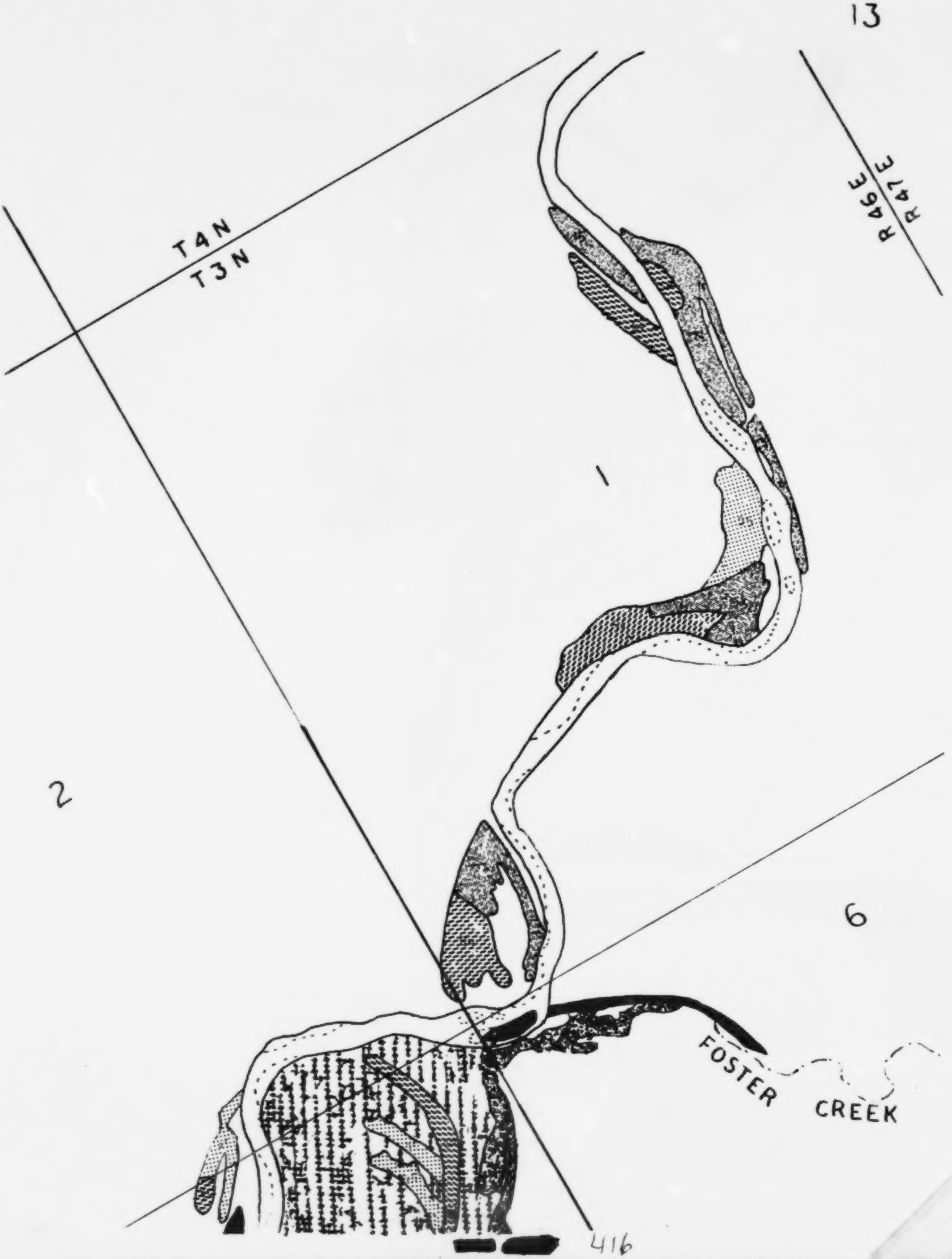
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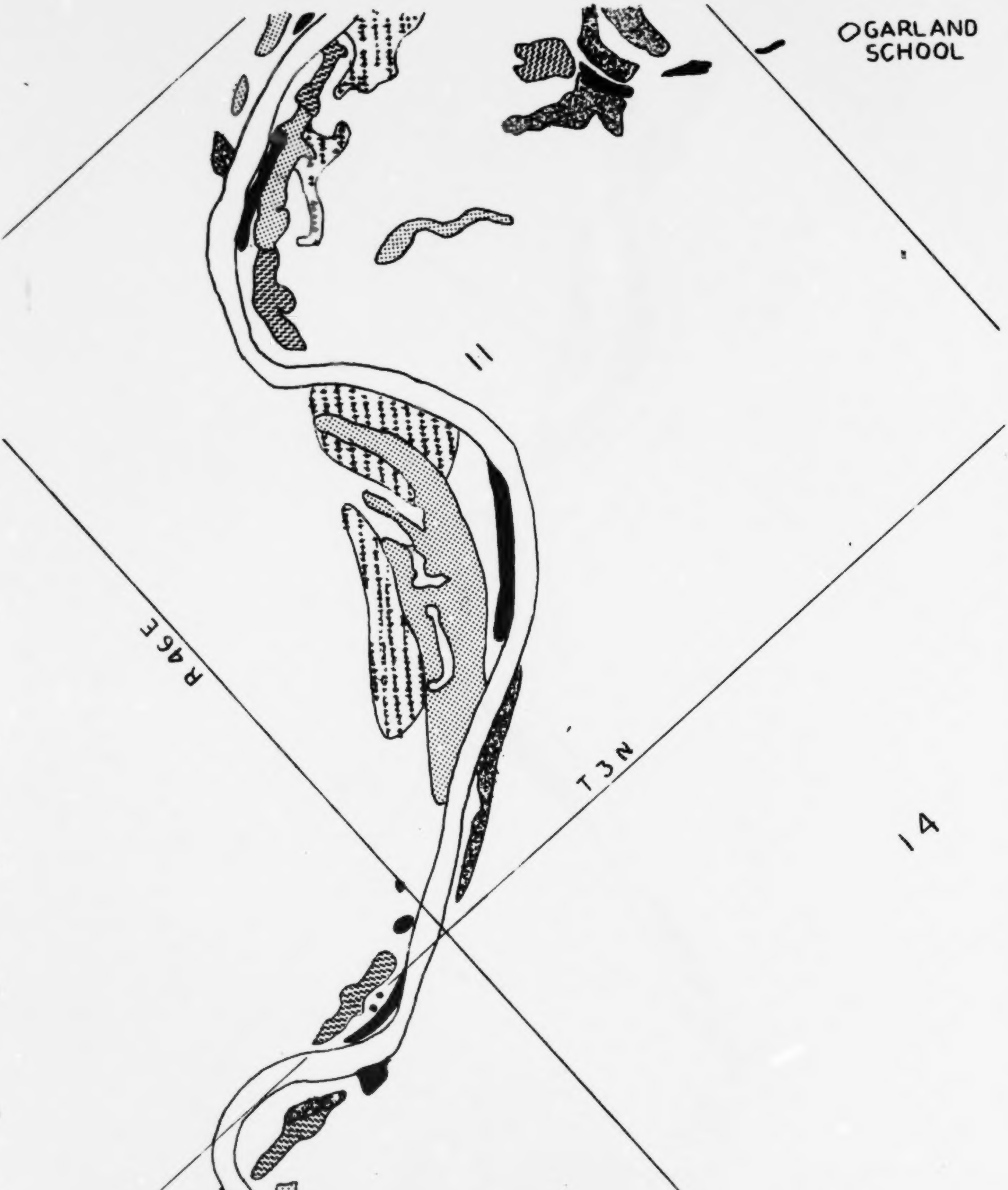
T3N
R46E
R47E
1
2
6
FOSTER CREEK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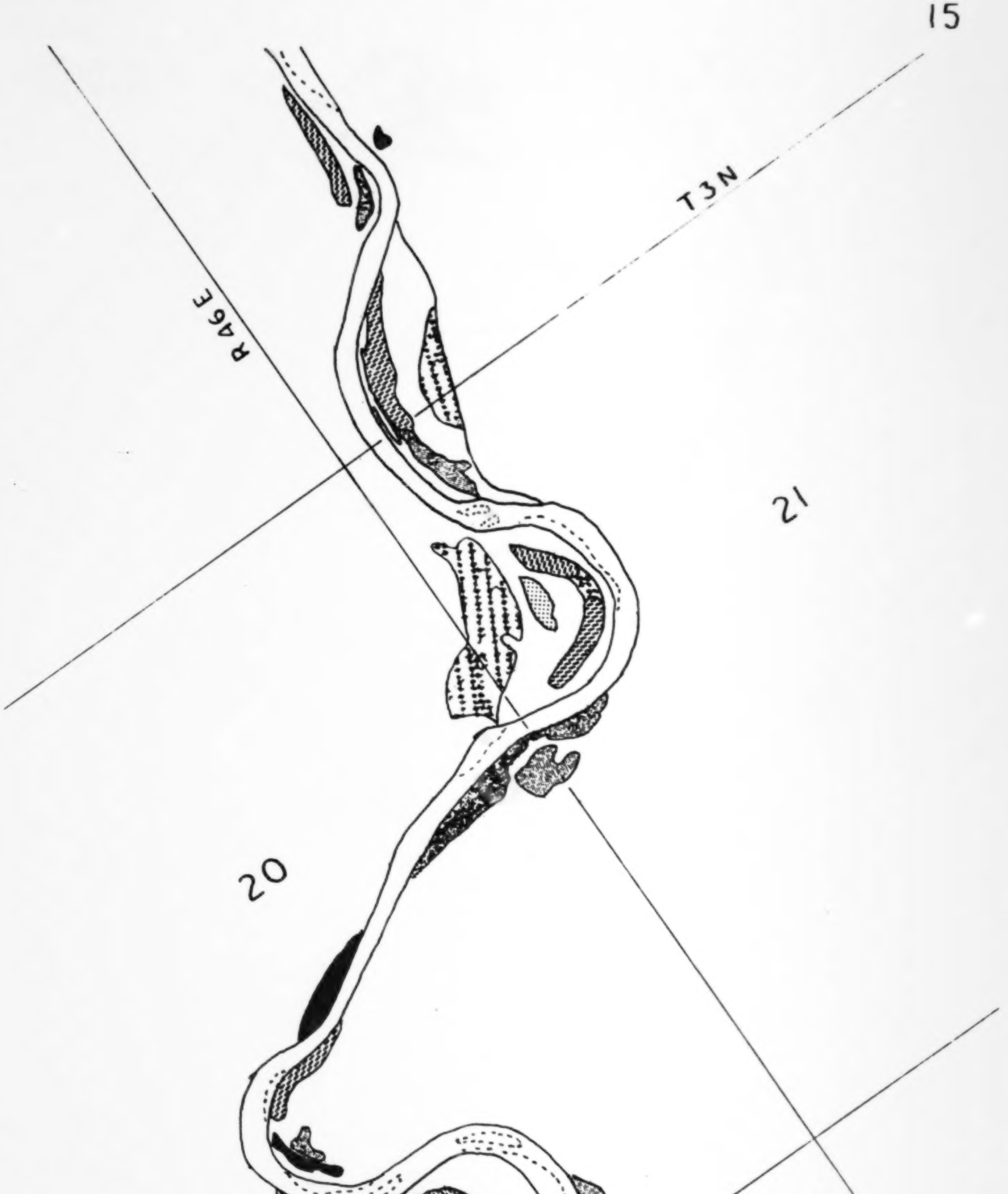
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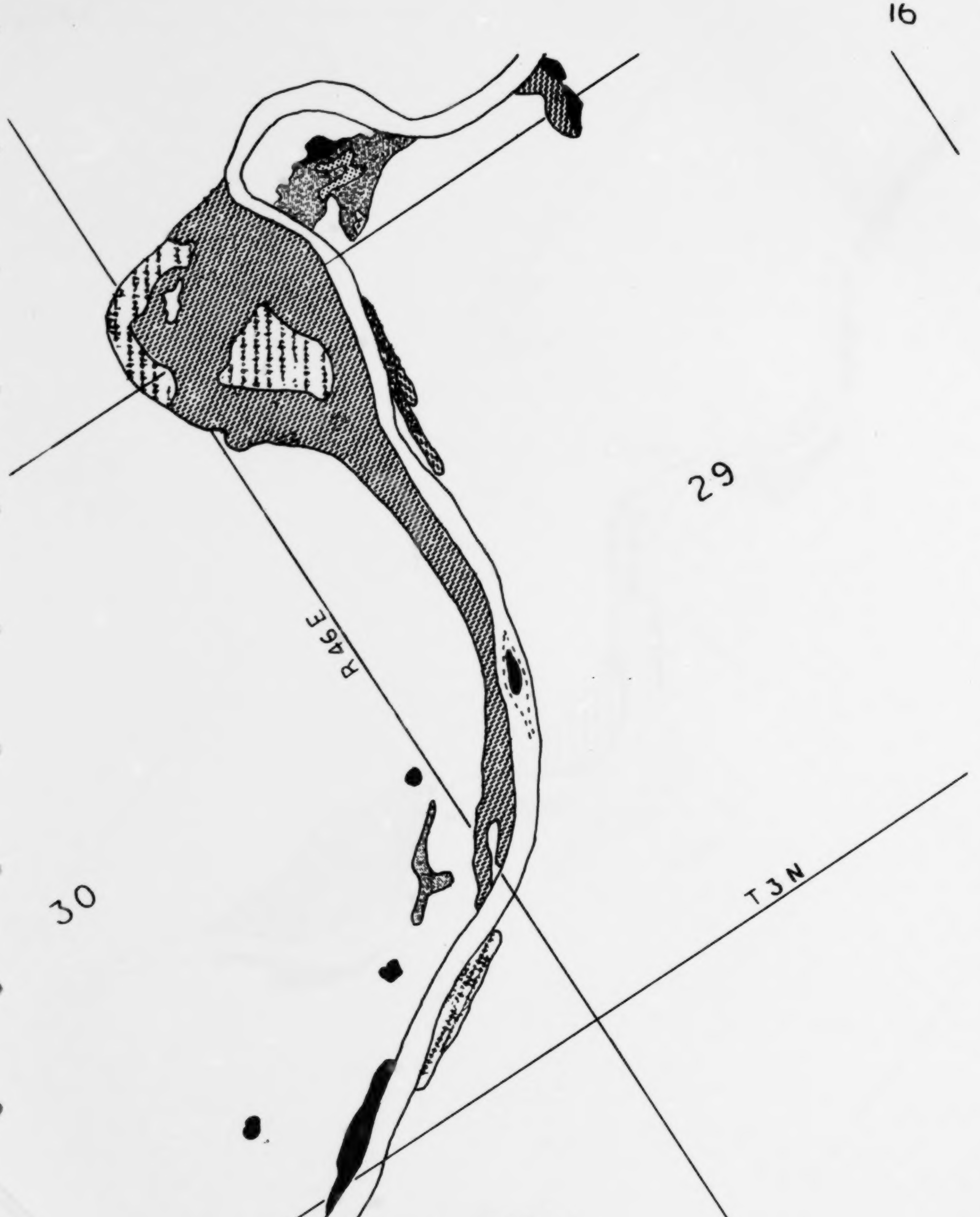
20



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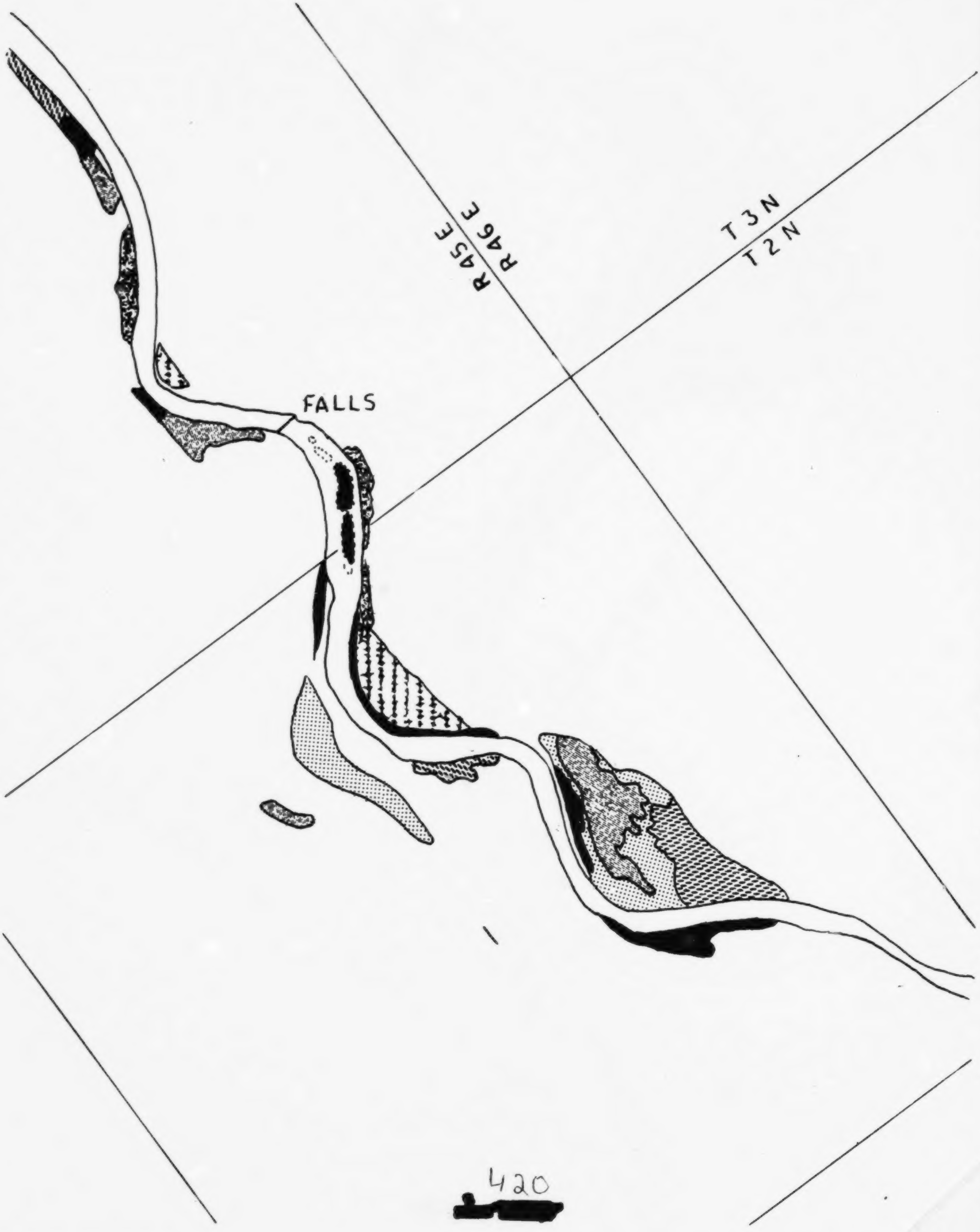
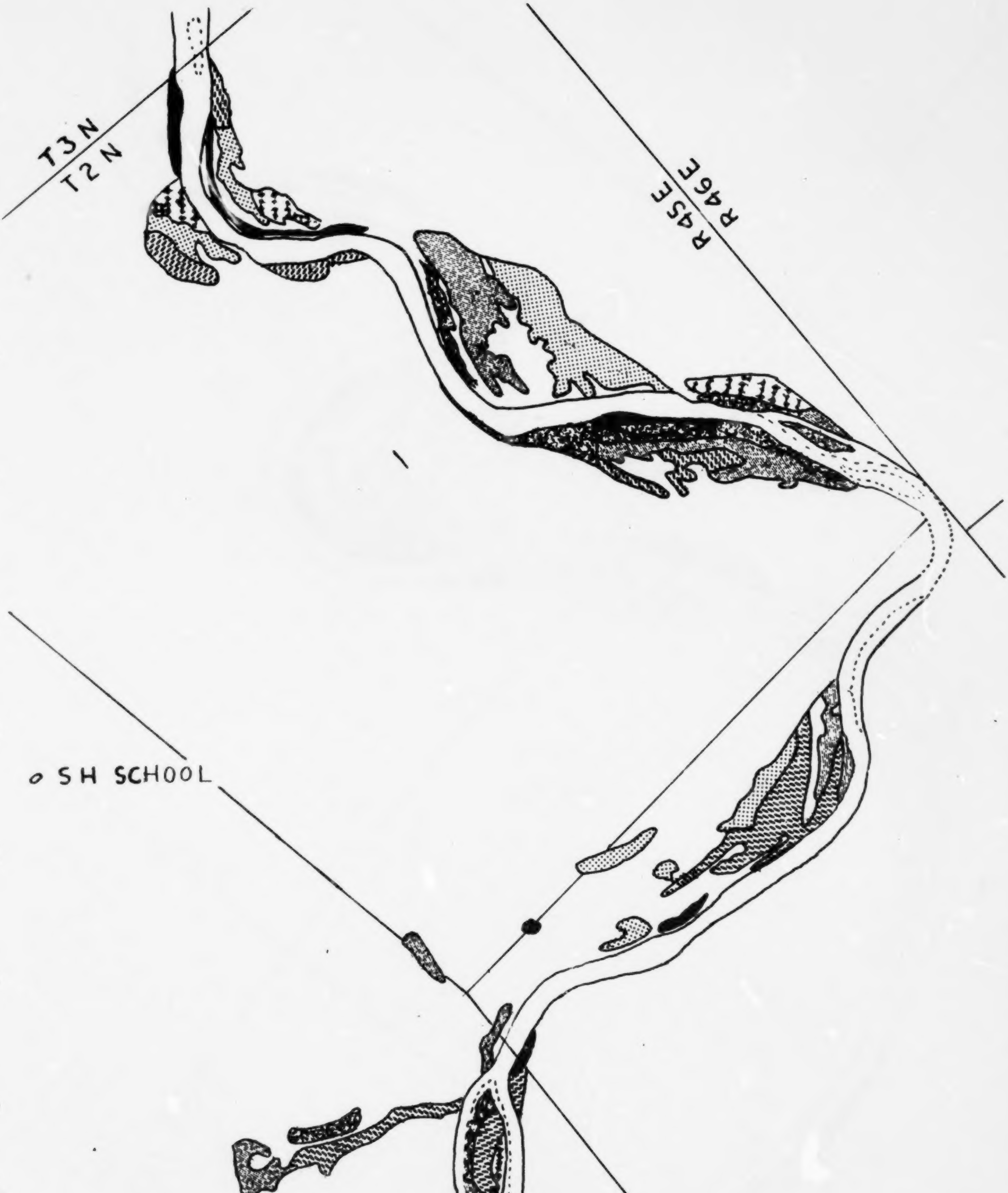

R45E
R46E
T3N
T2N
FALLS
420



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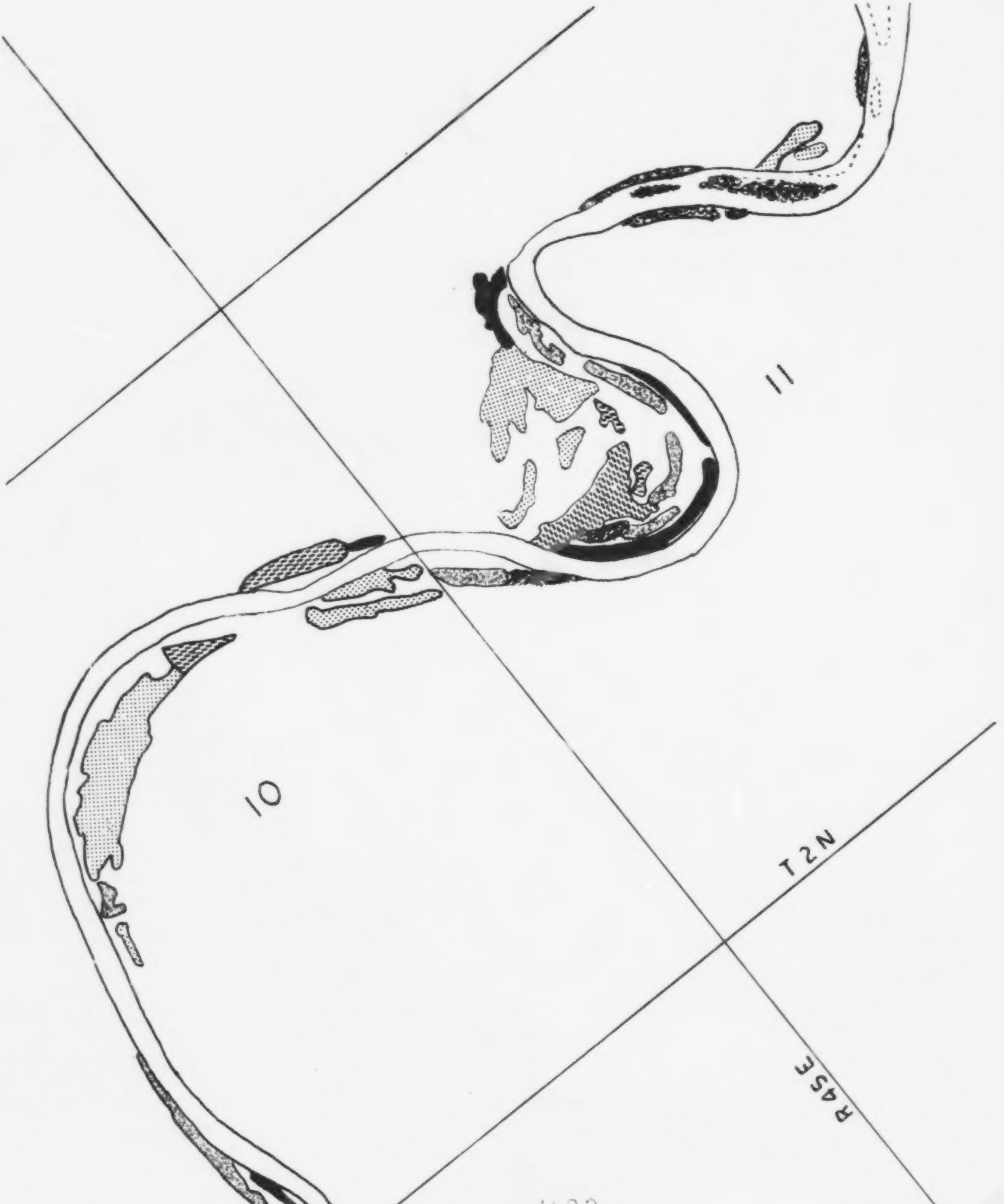
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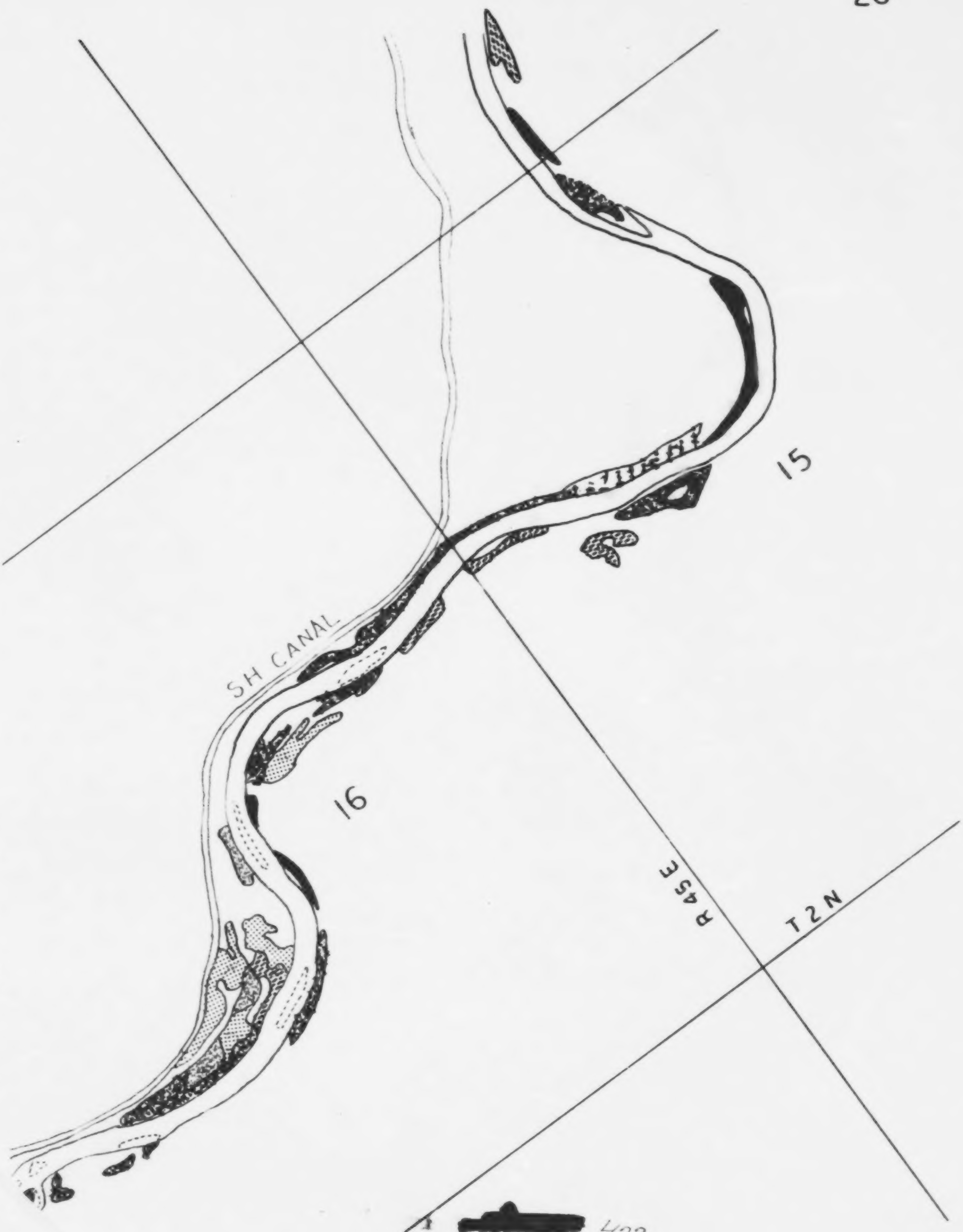

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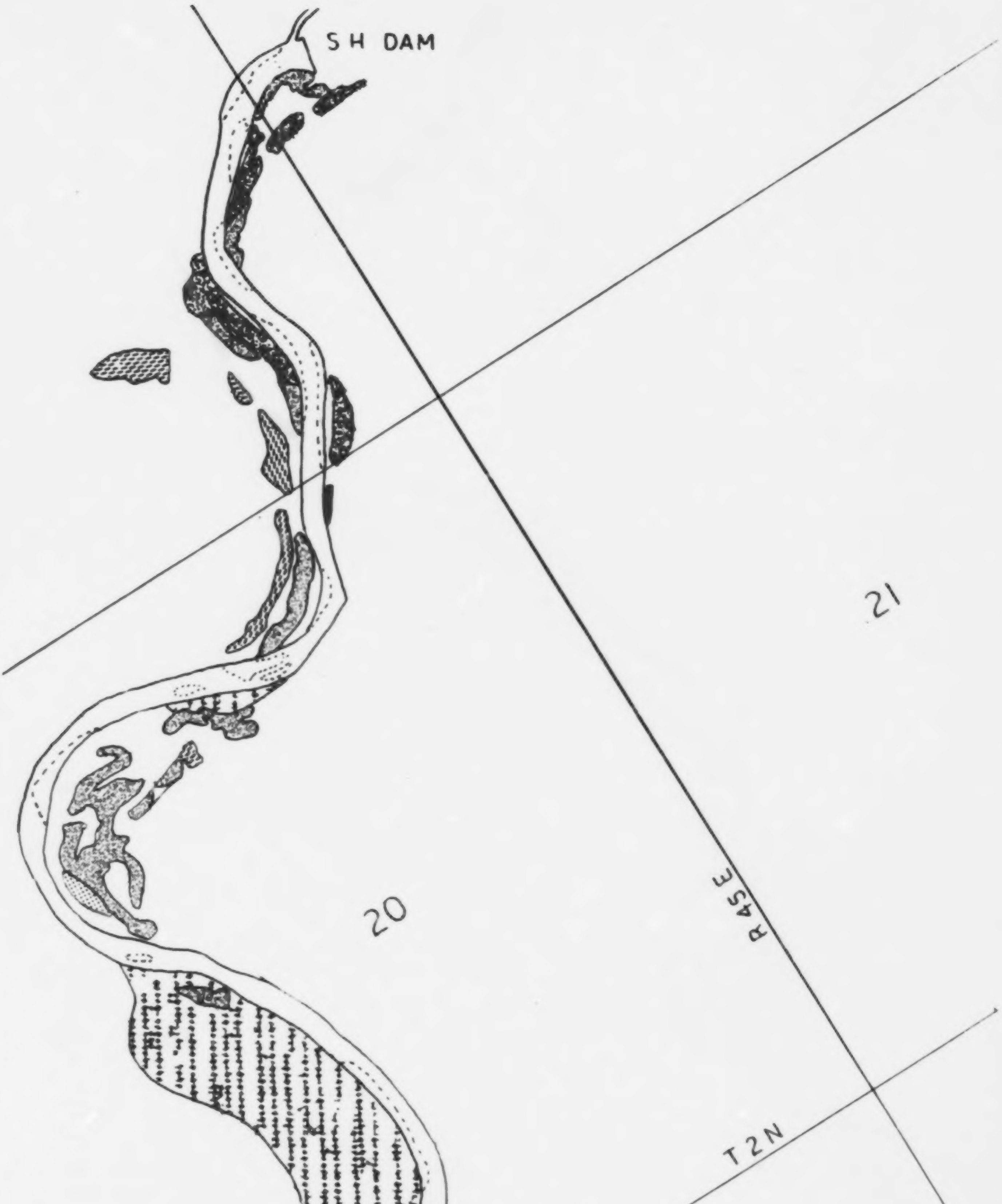

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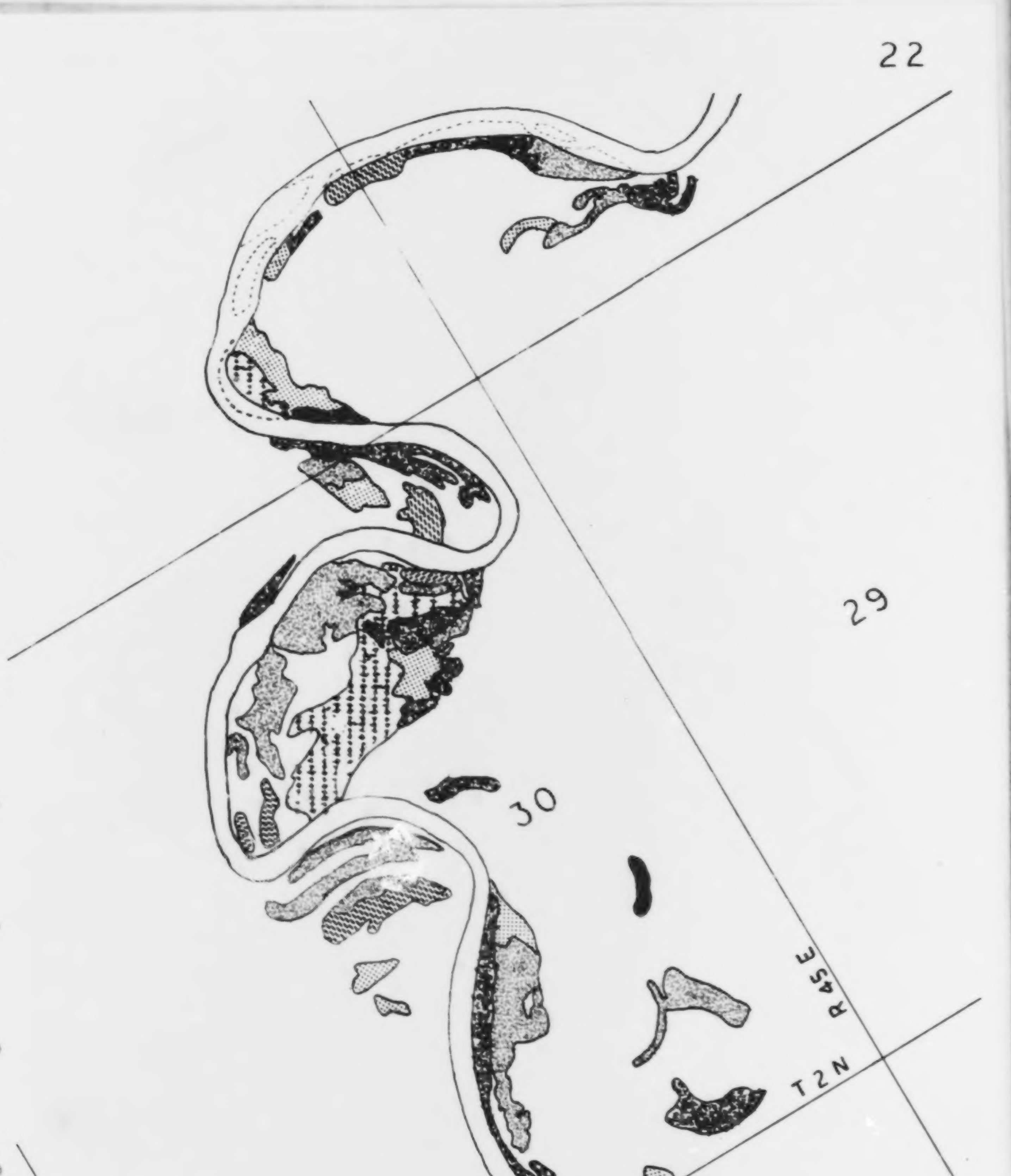
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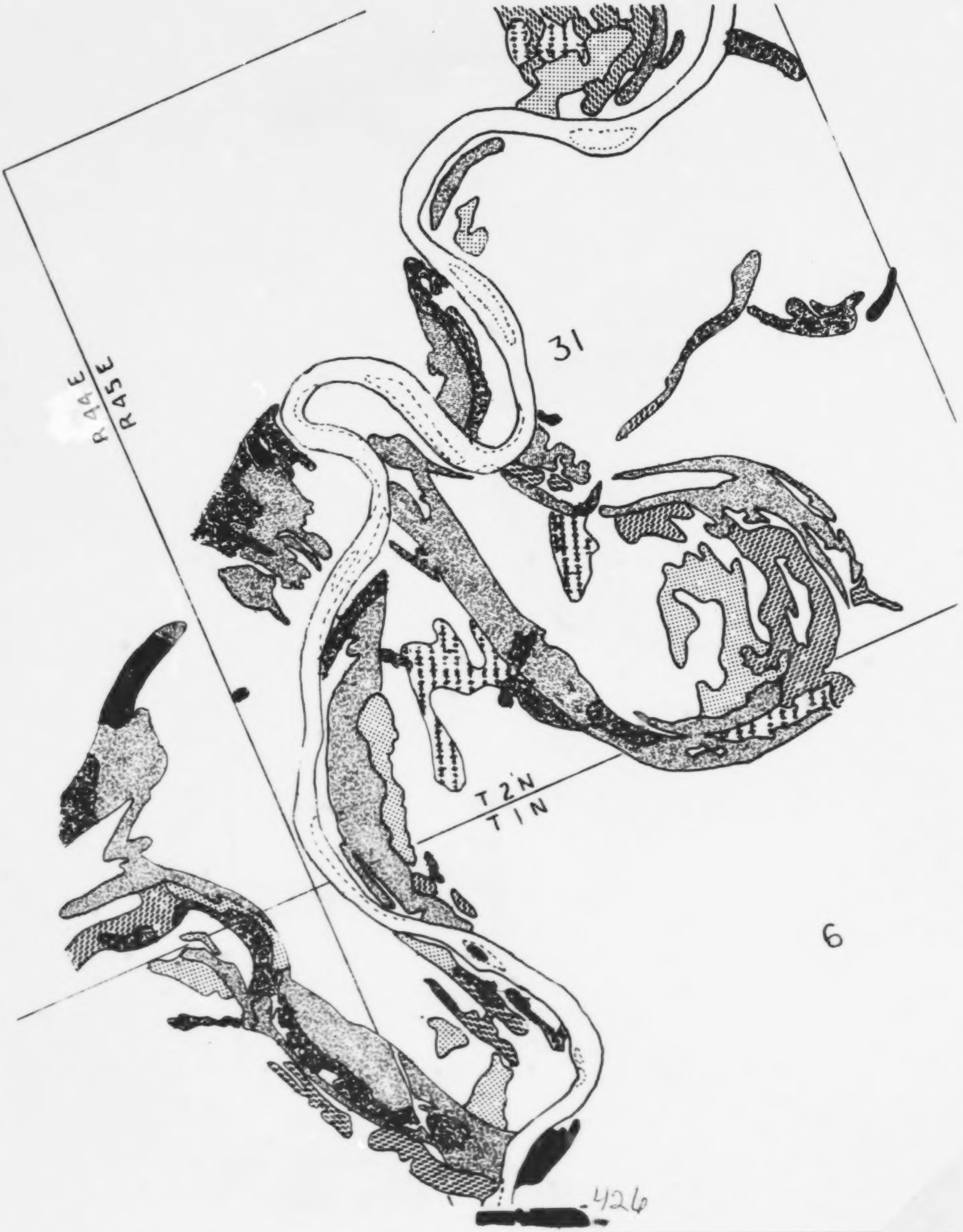
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T2N
T1N
6
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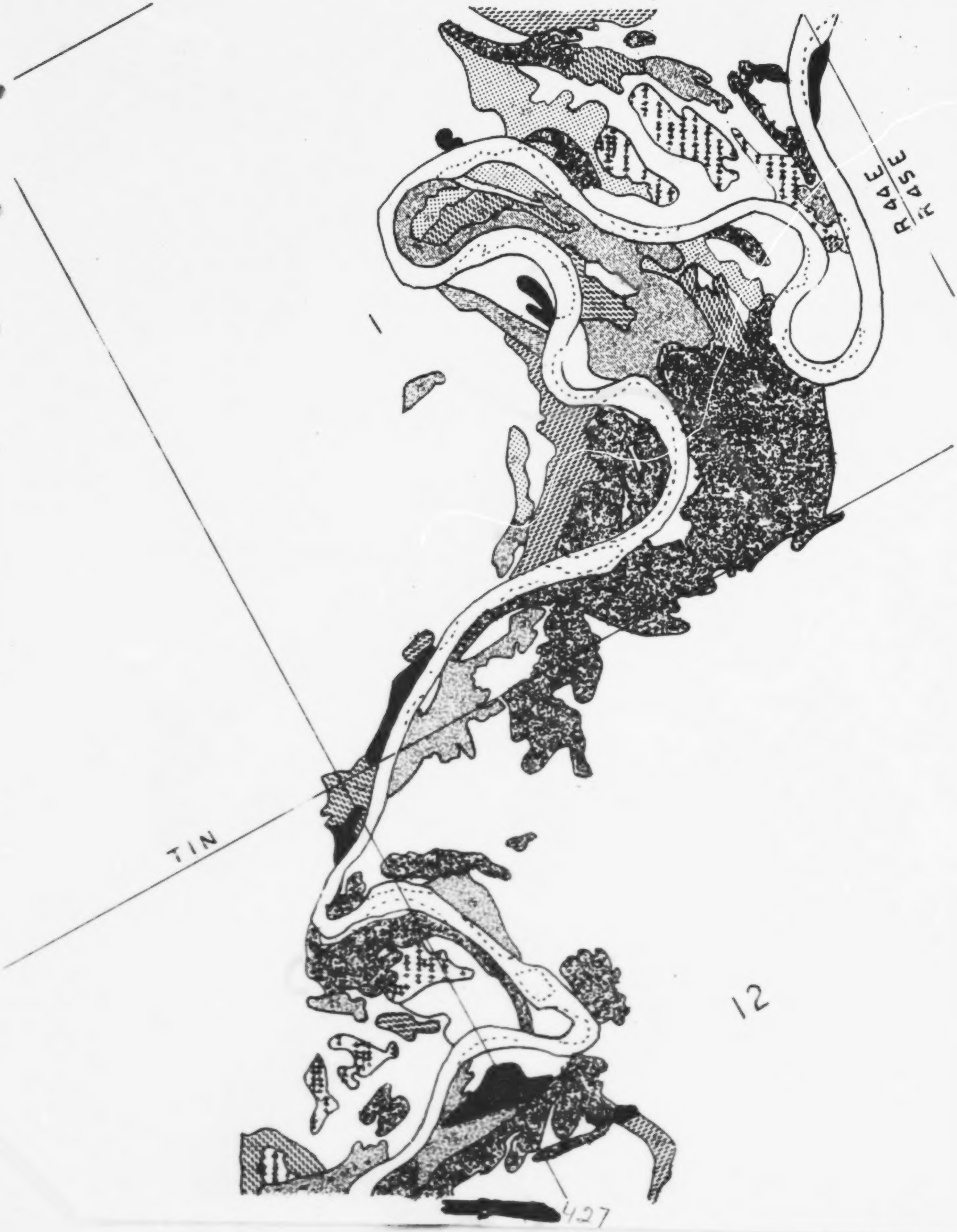
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R45E
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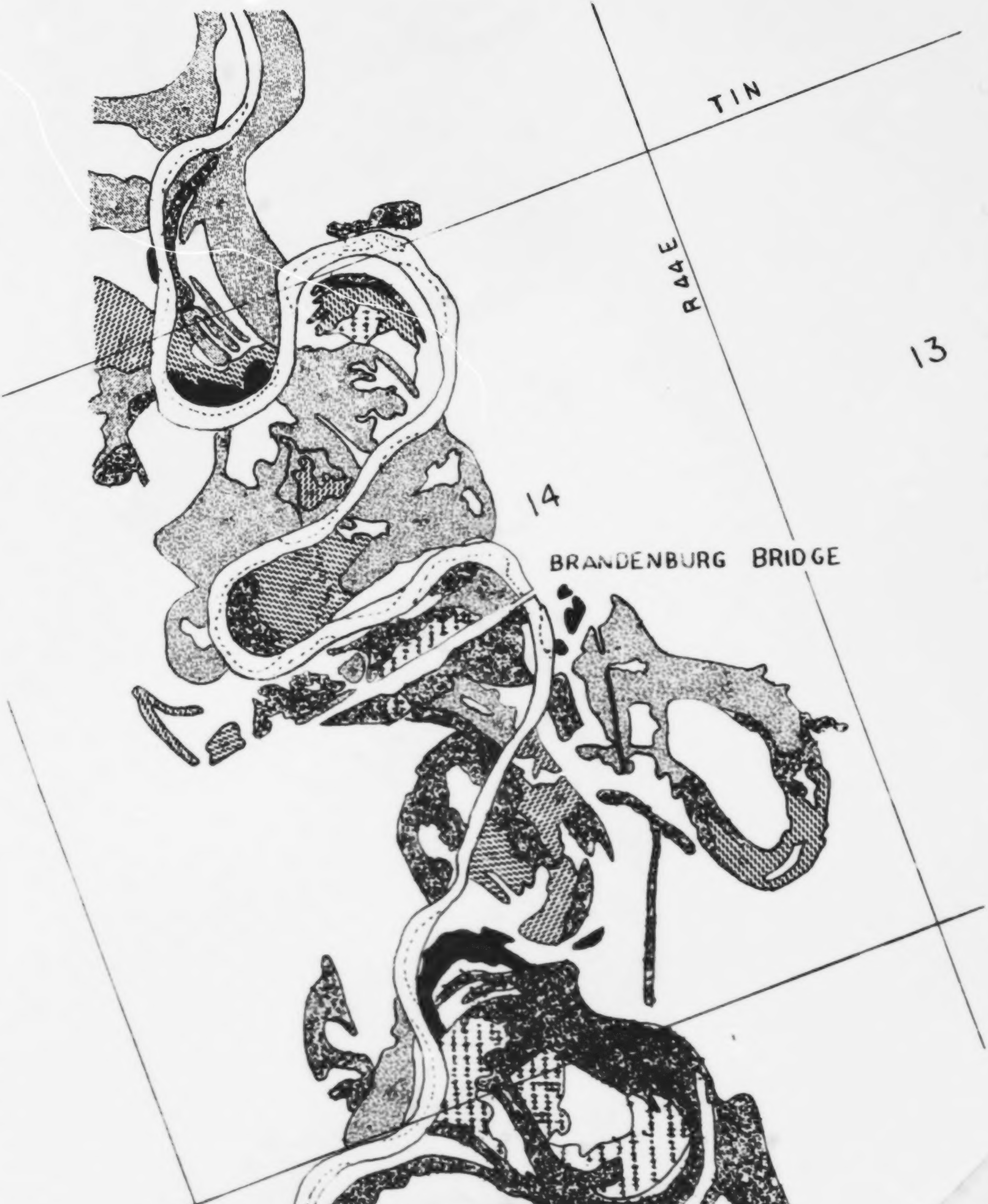
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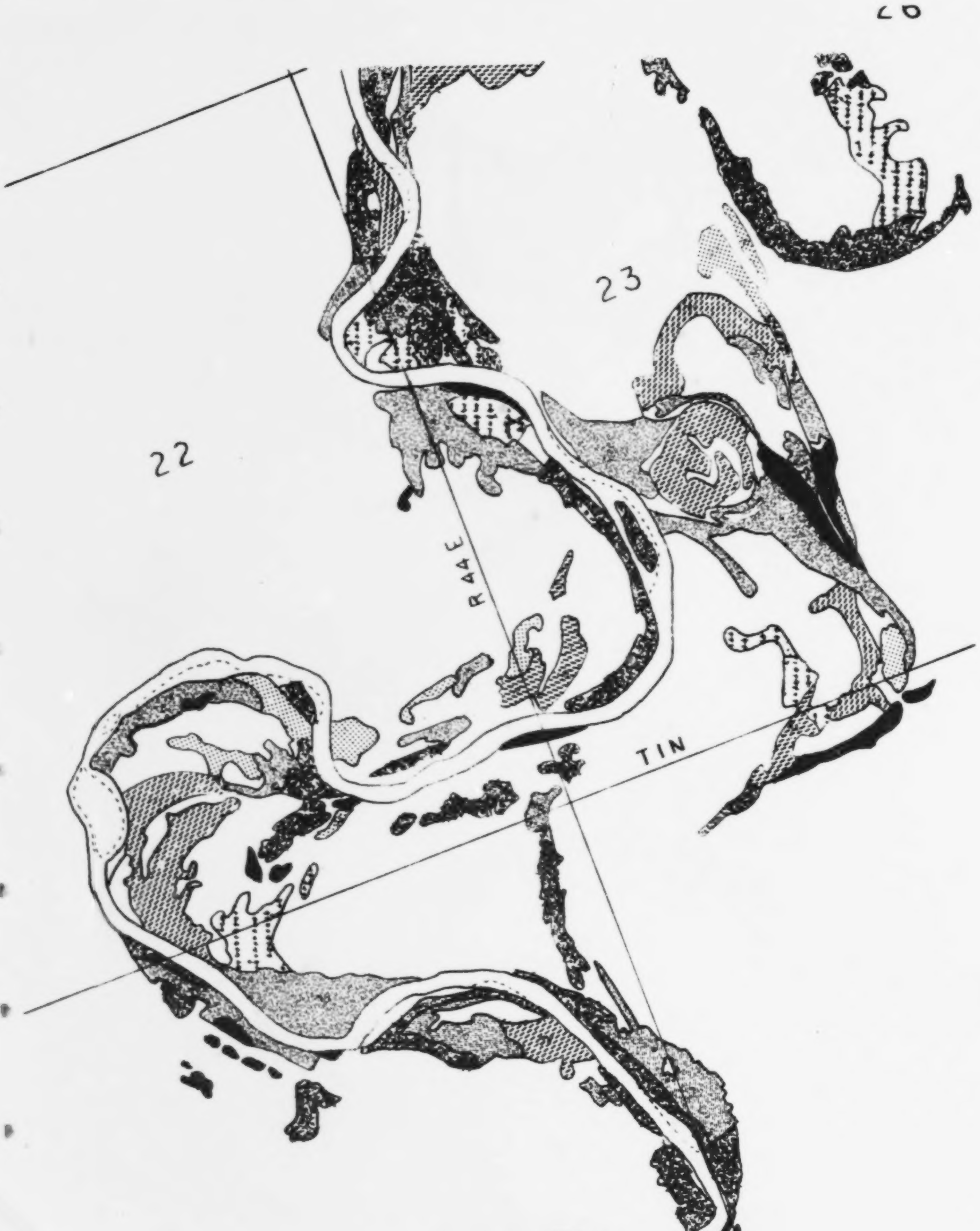
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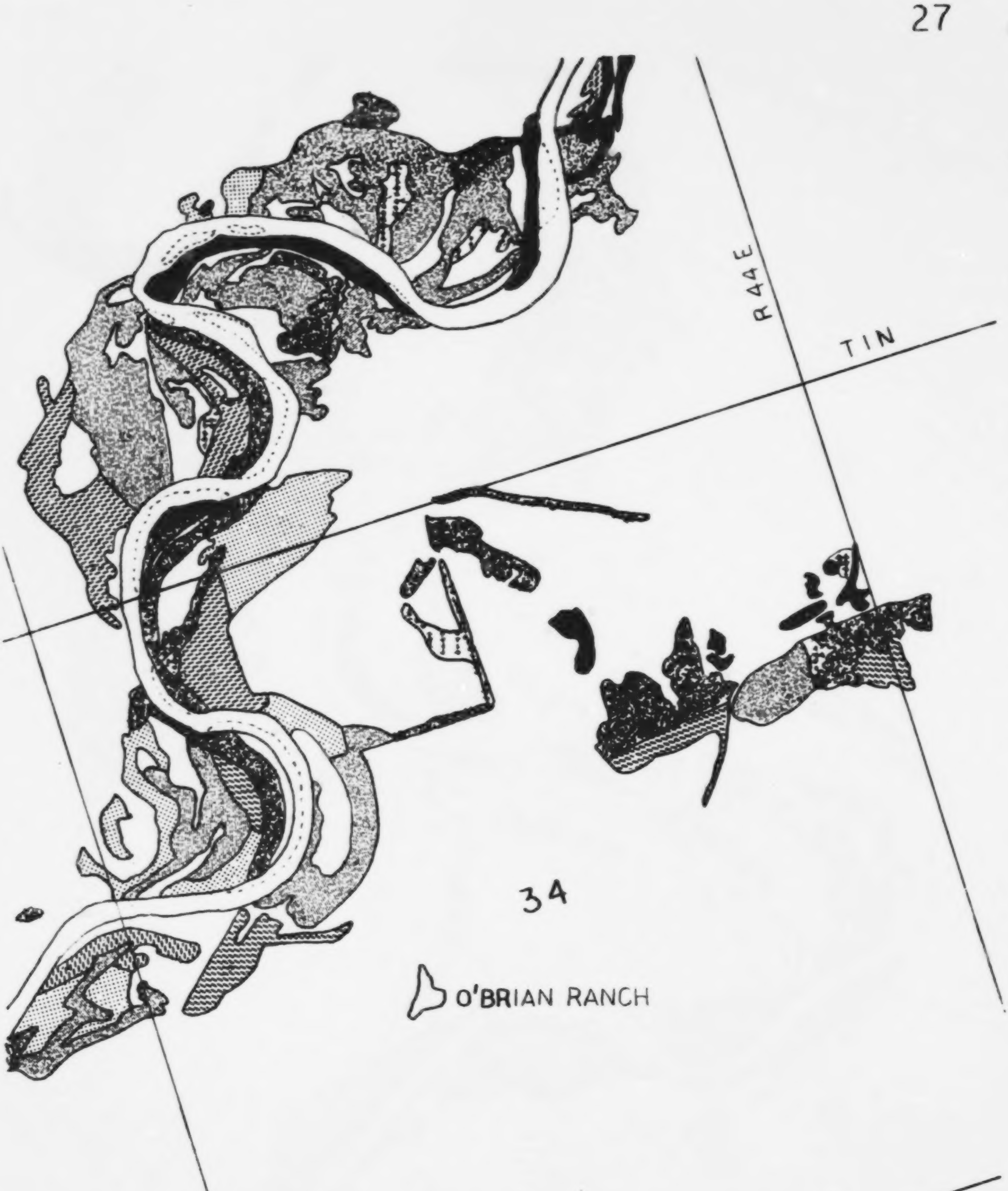
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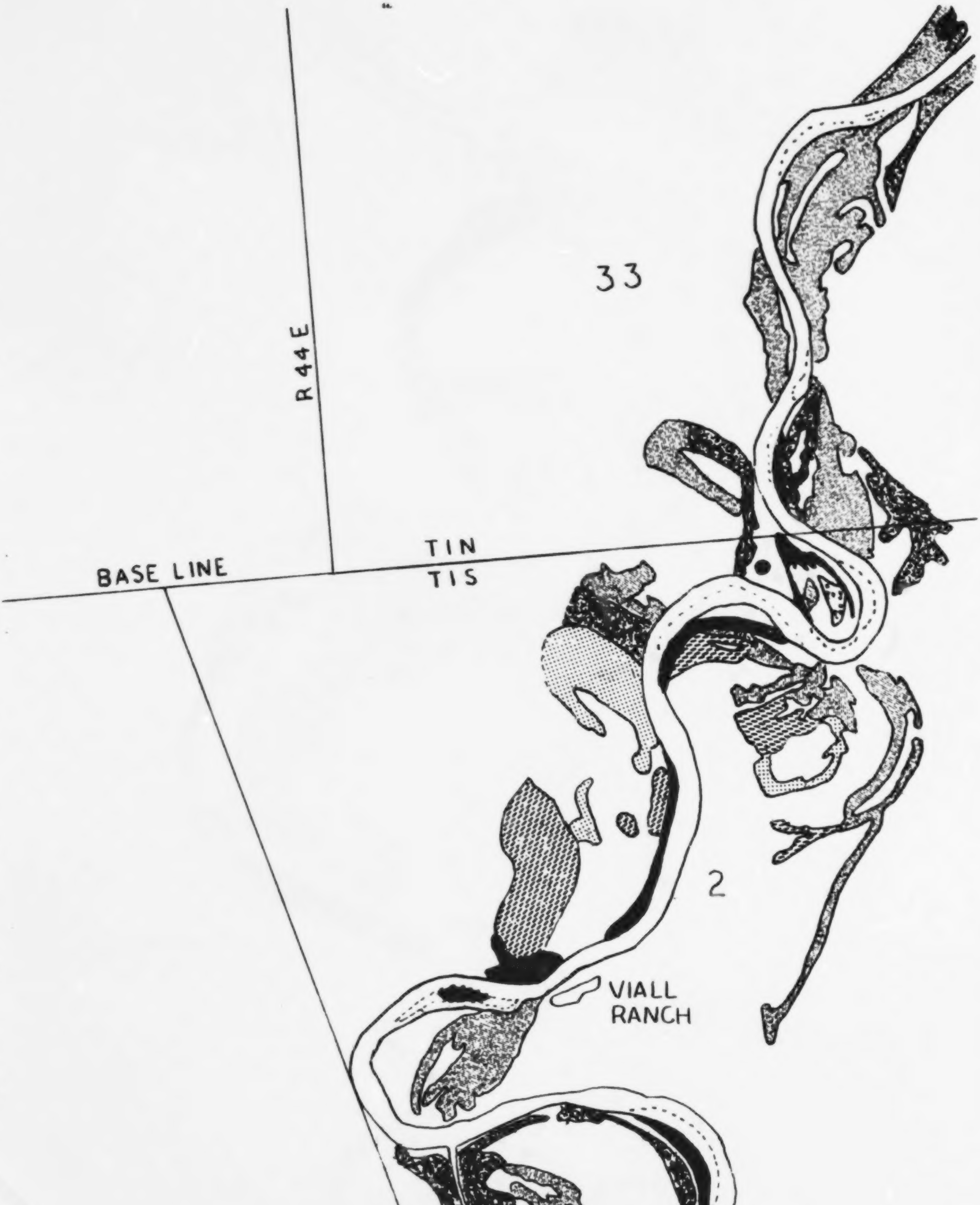

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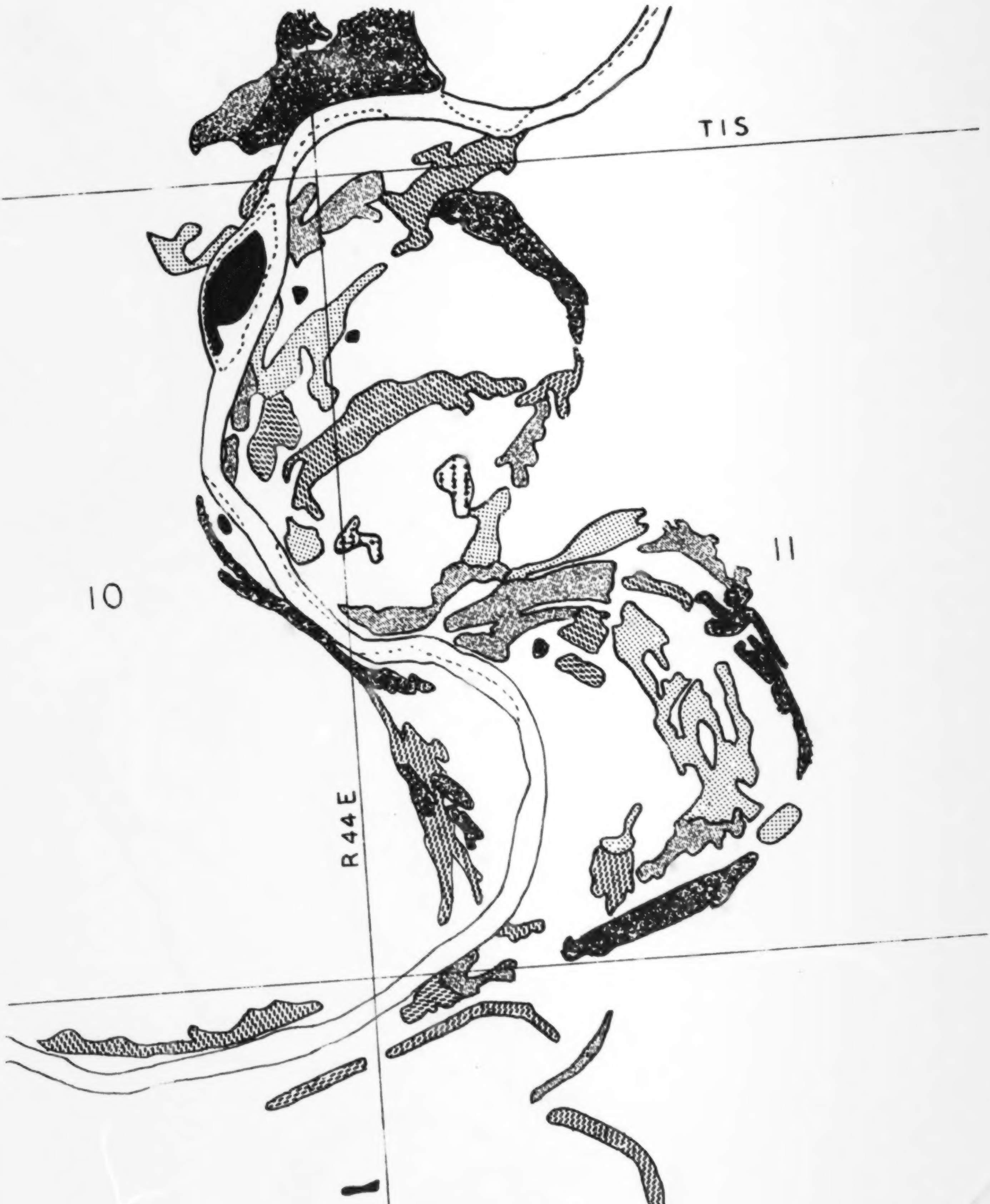
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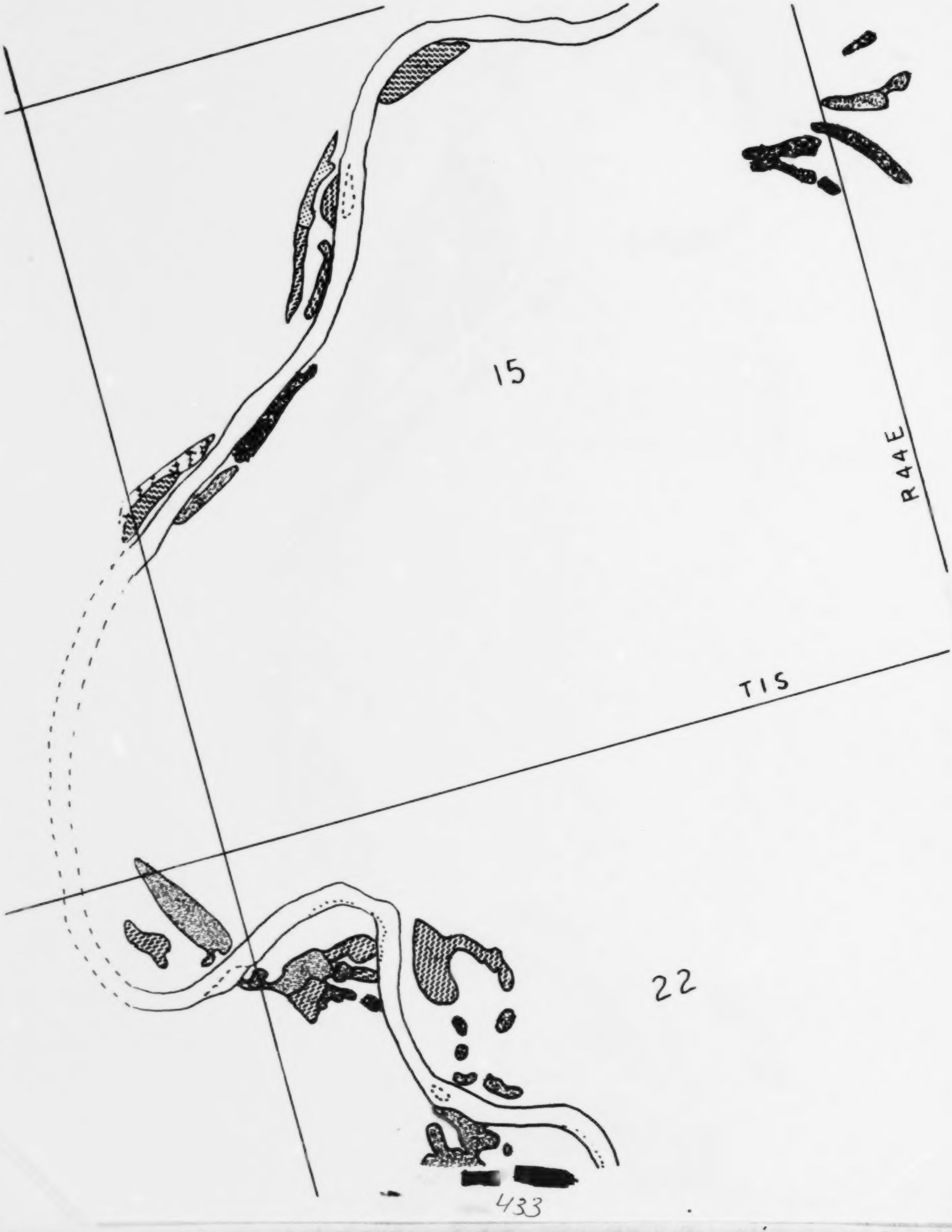
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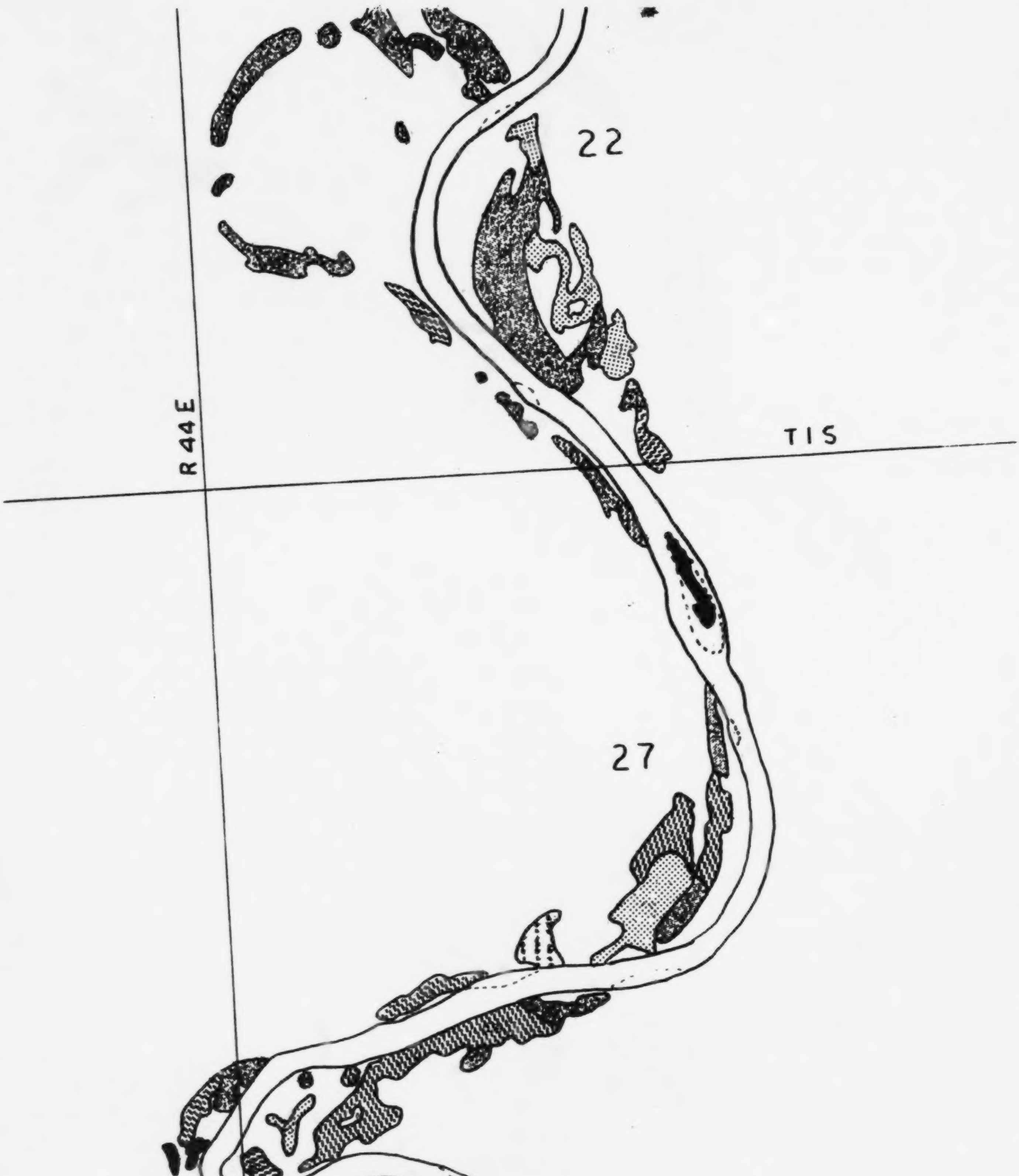
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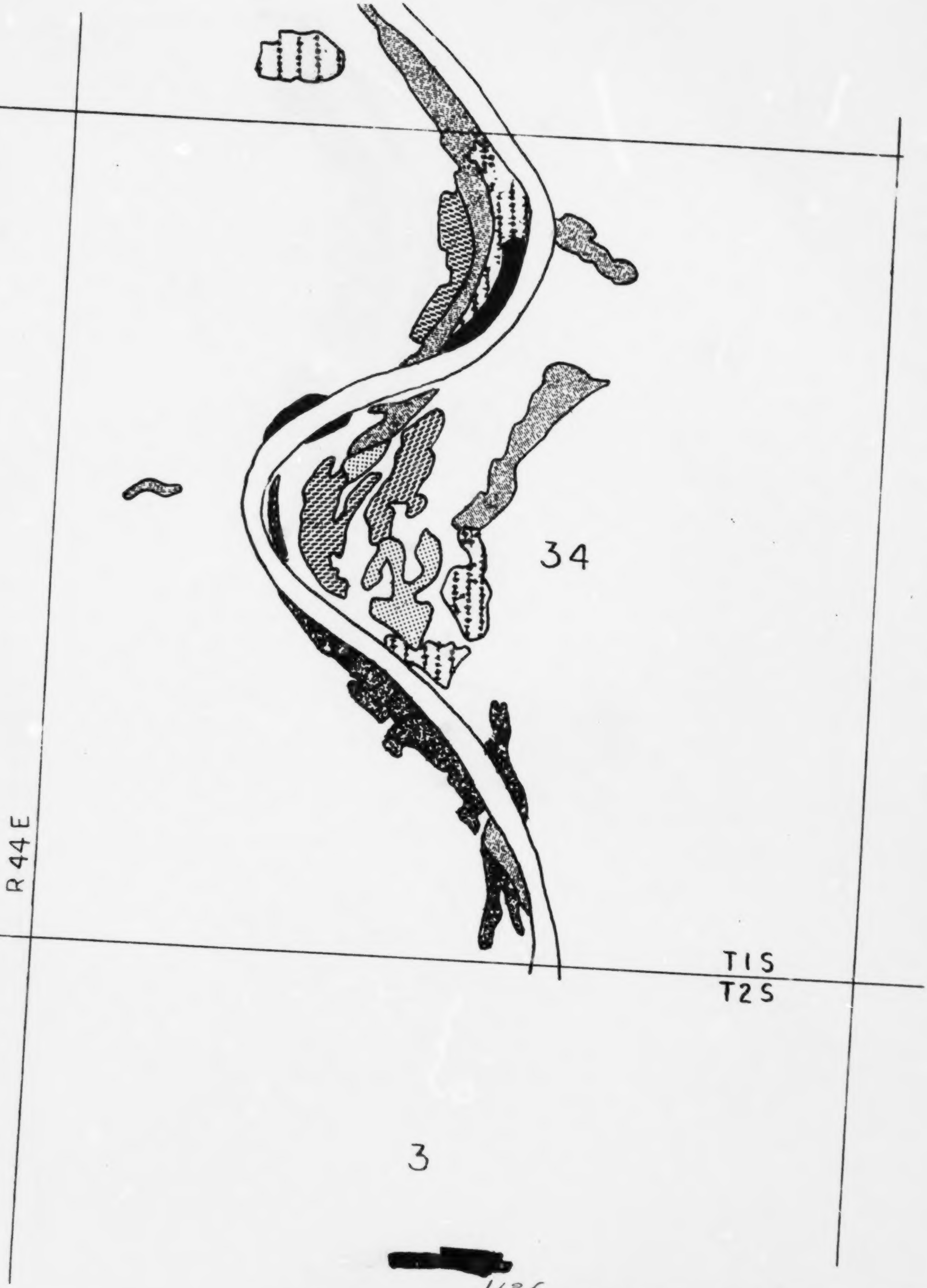

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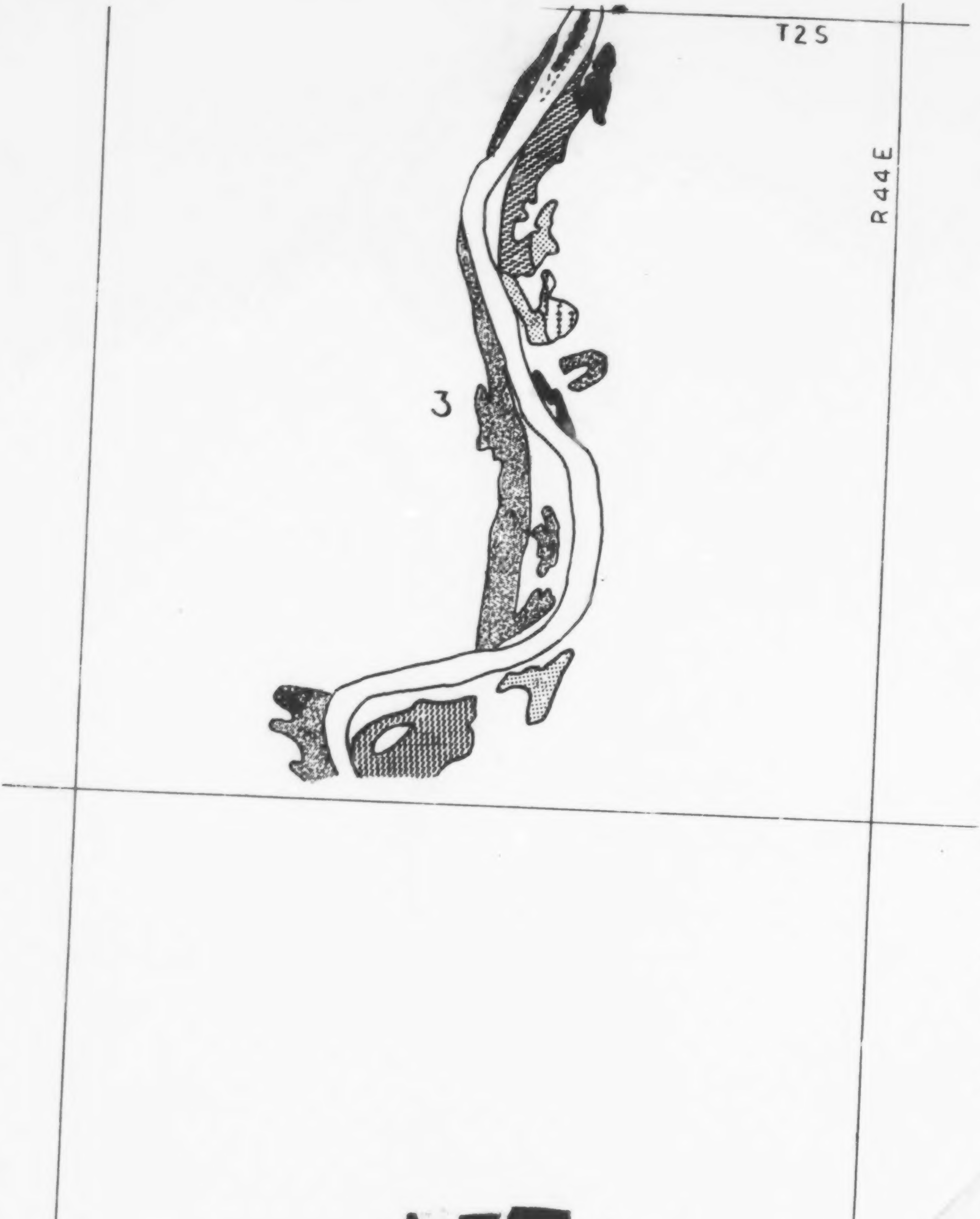
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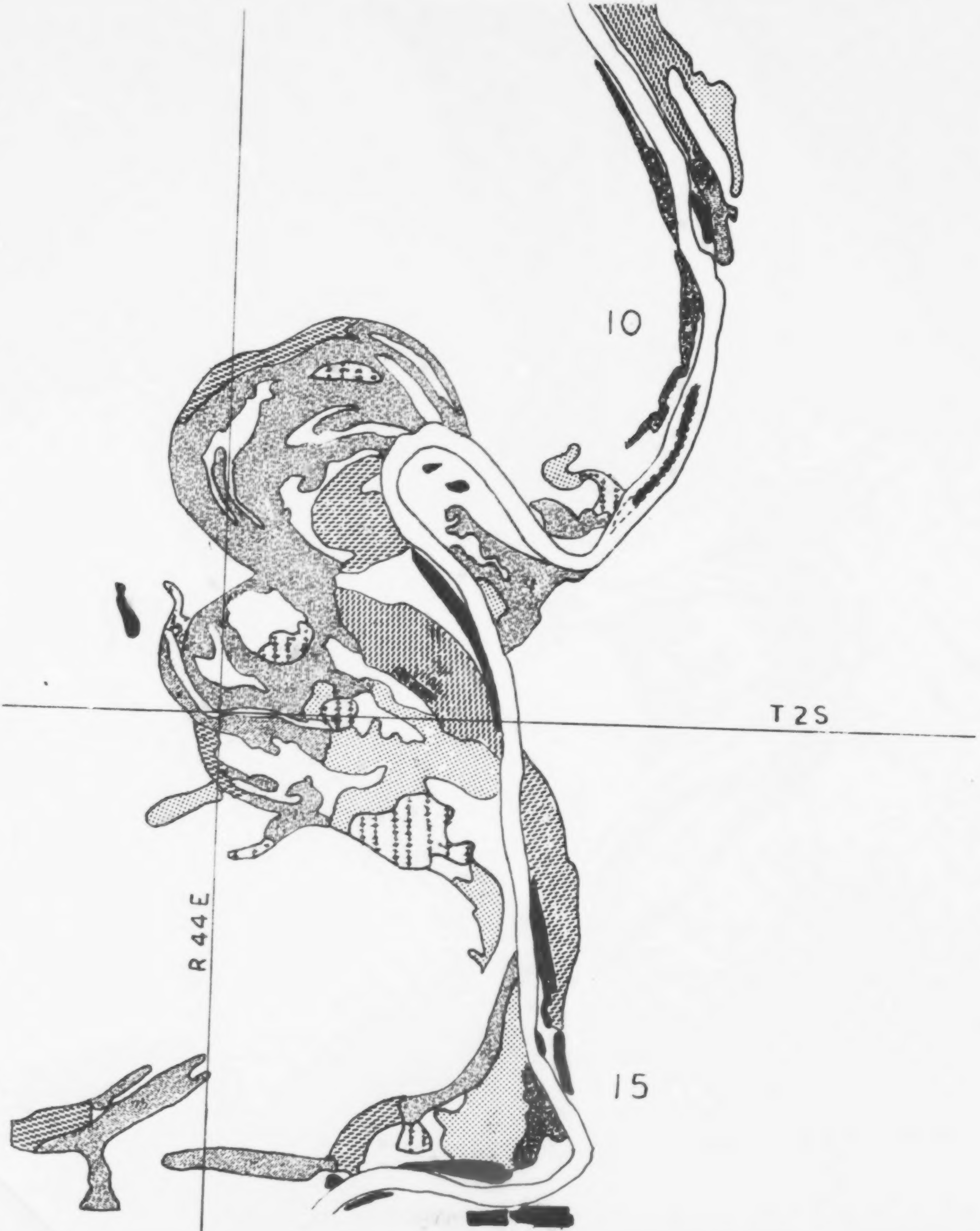

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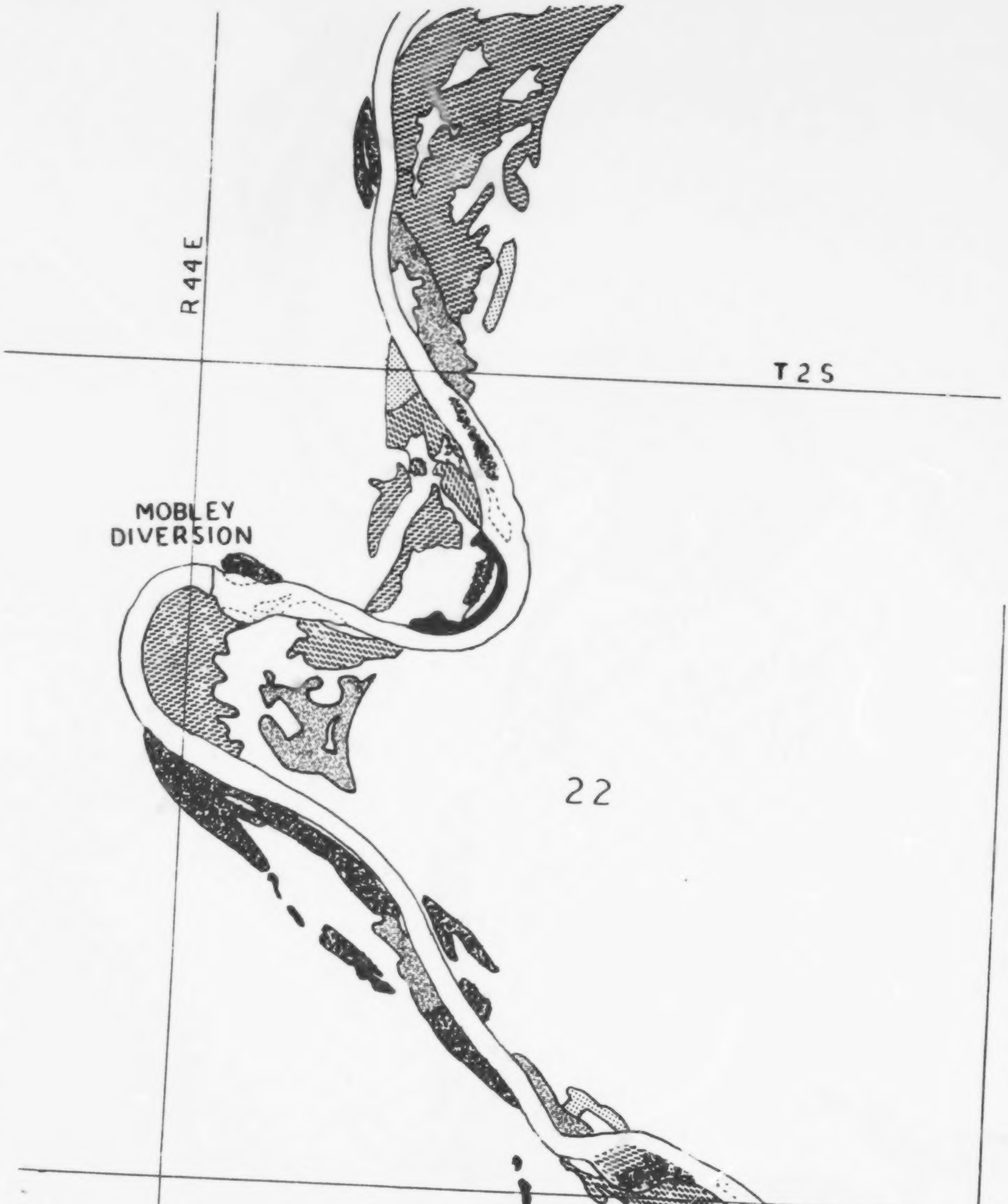
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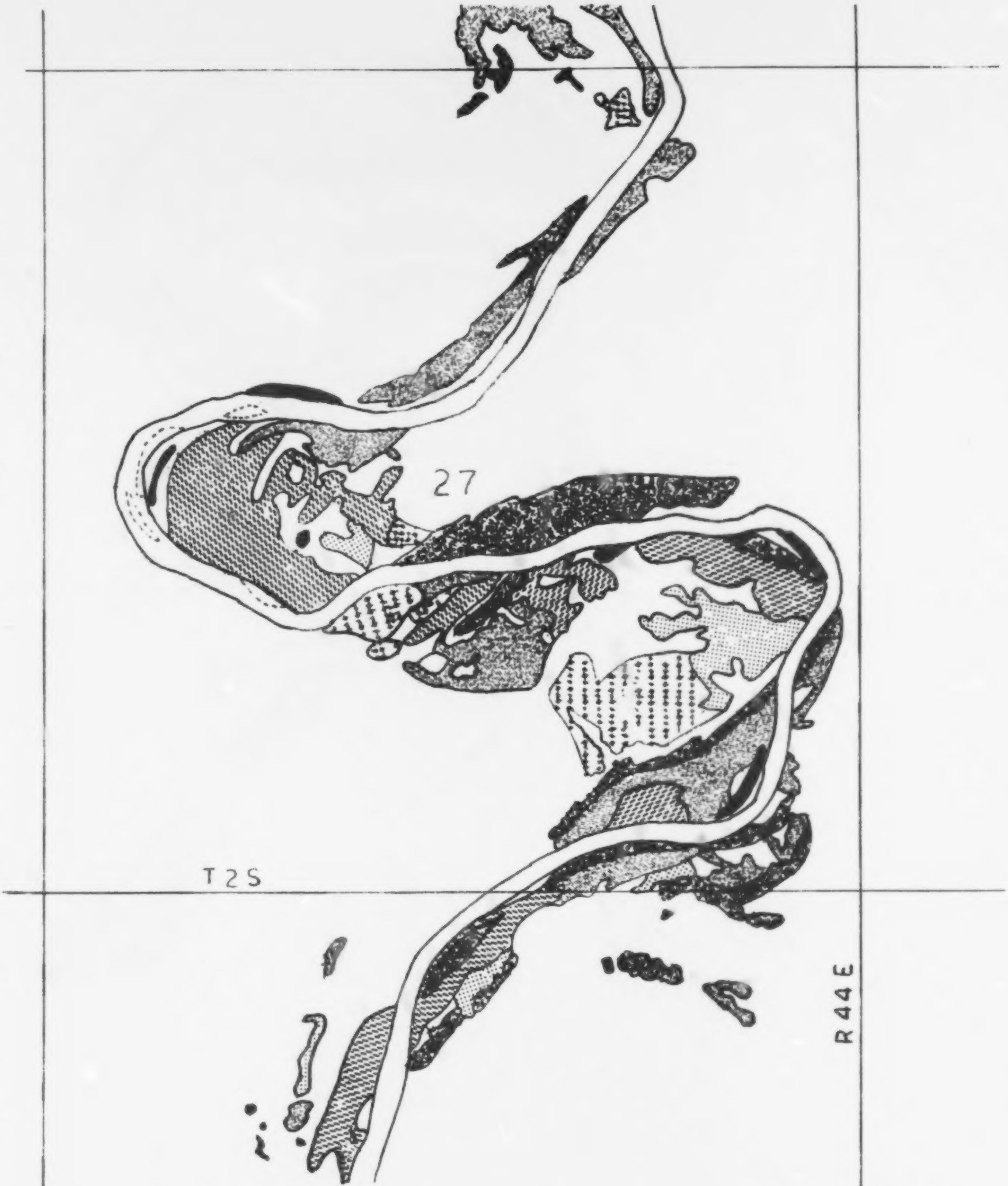

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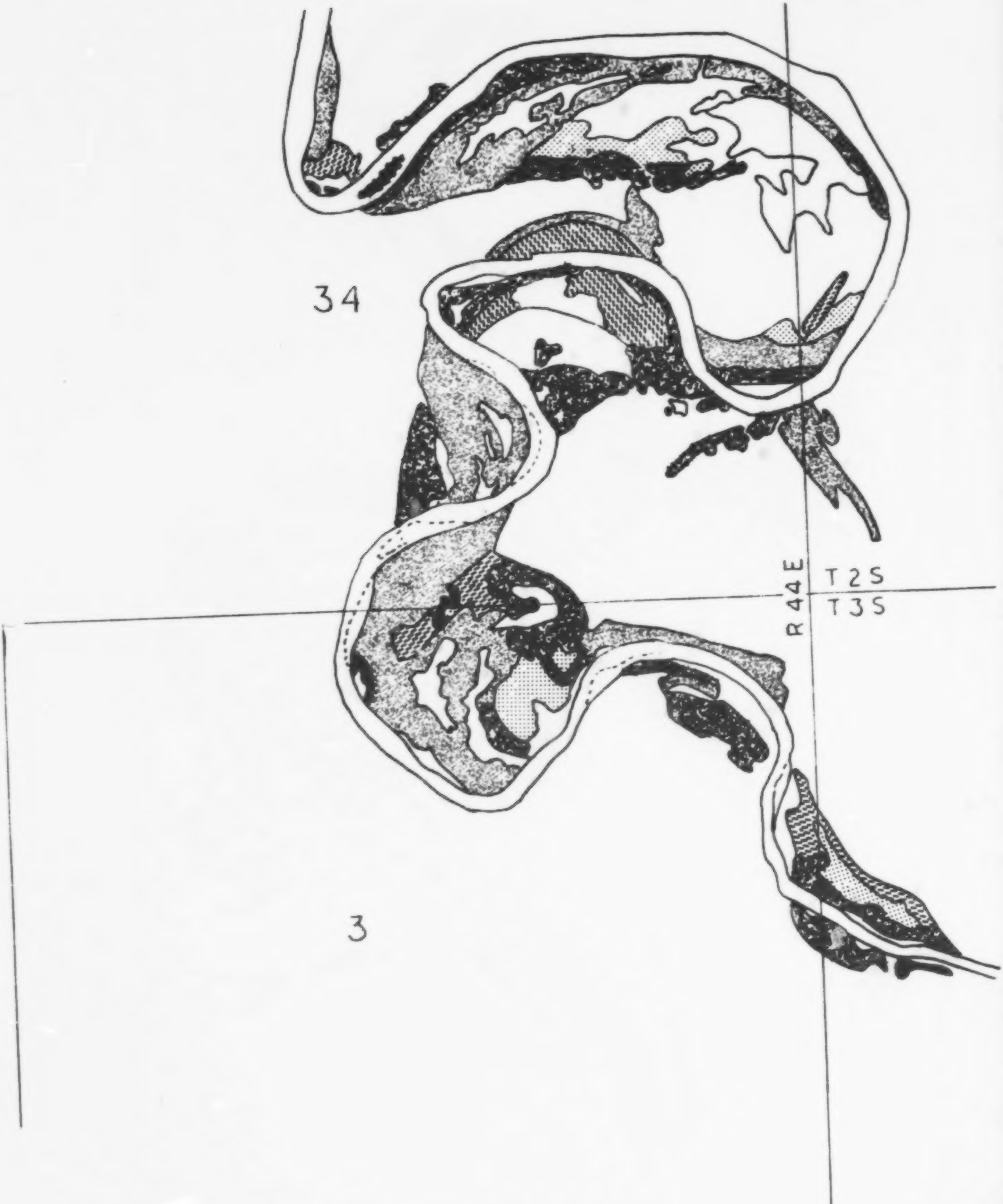
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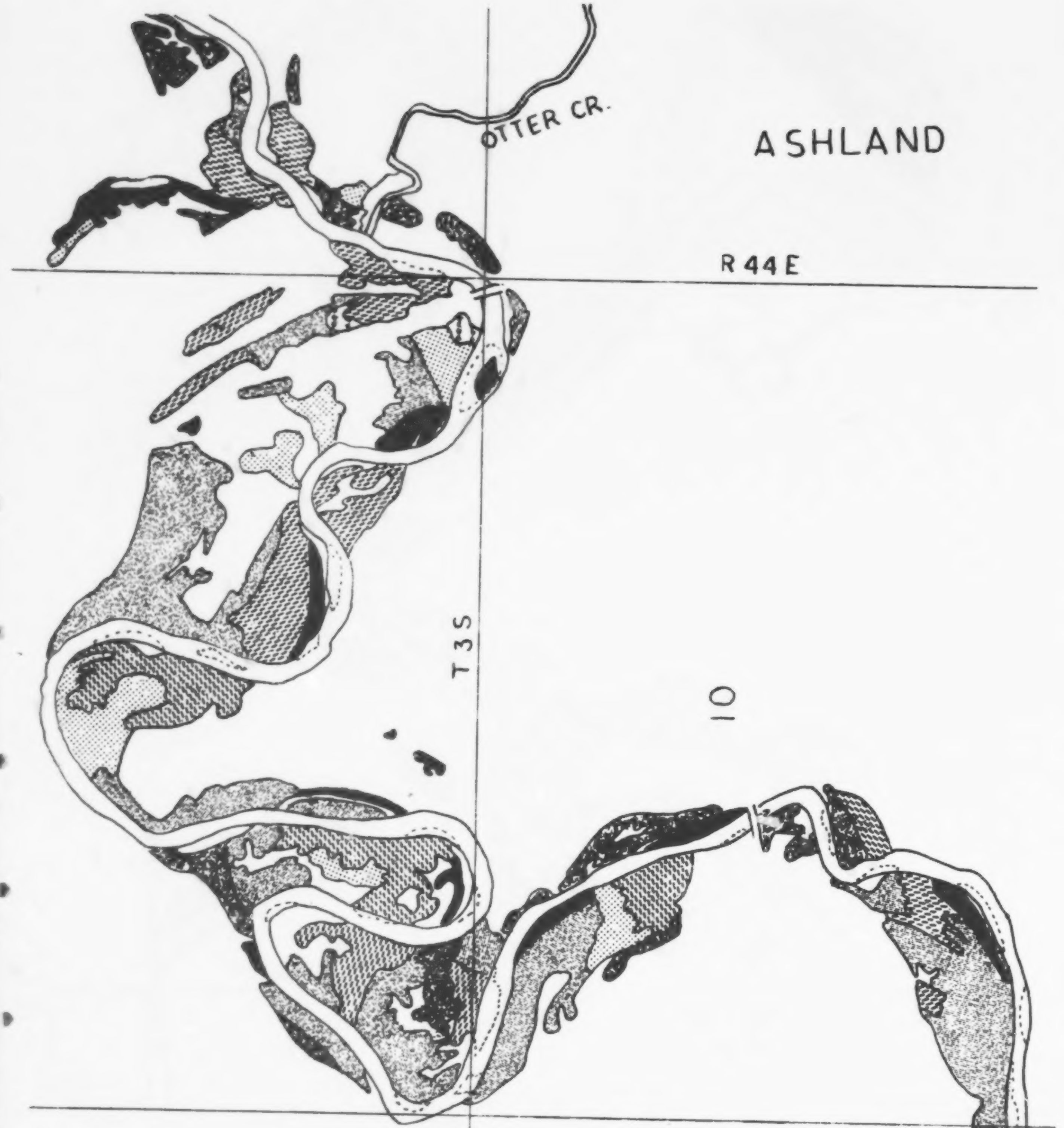
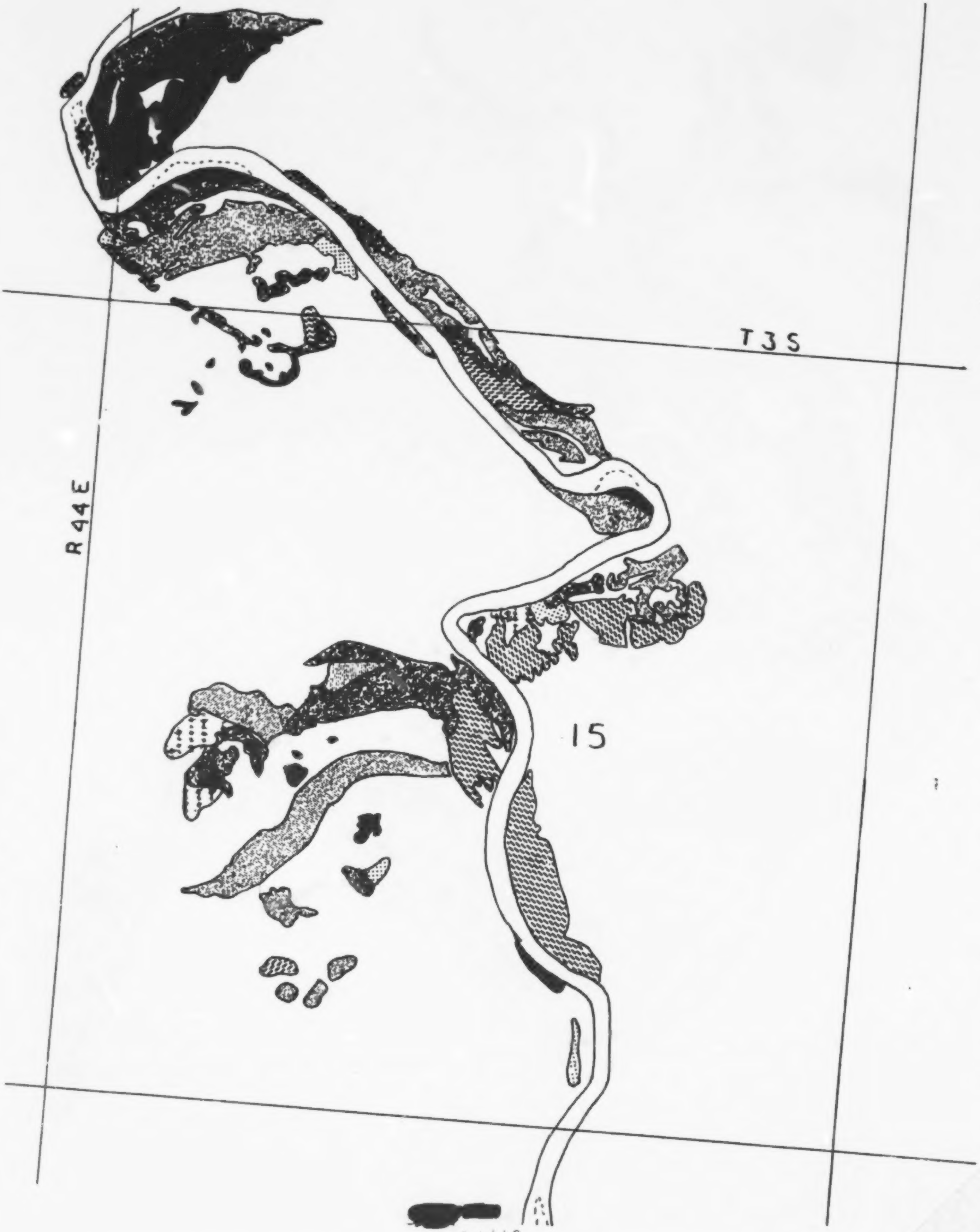
T 2 S
T 3 S
3


OTTER CR.
ASHLAND
R 44 E
T 3 S
10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R 44 E
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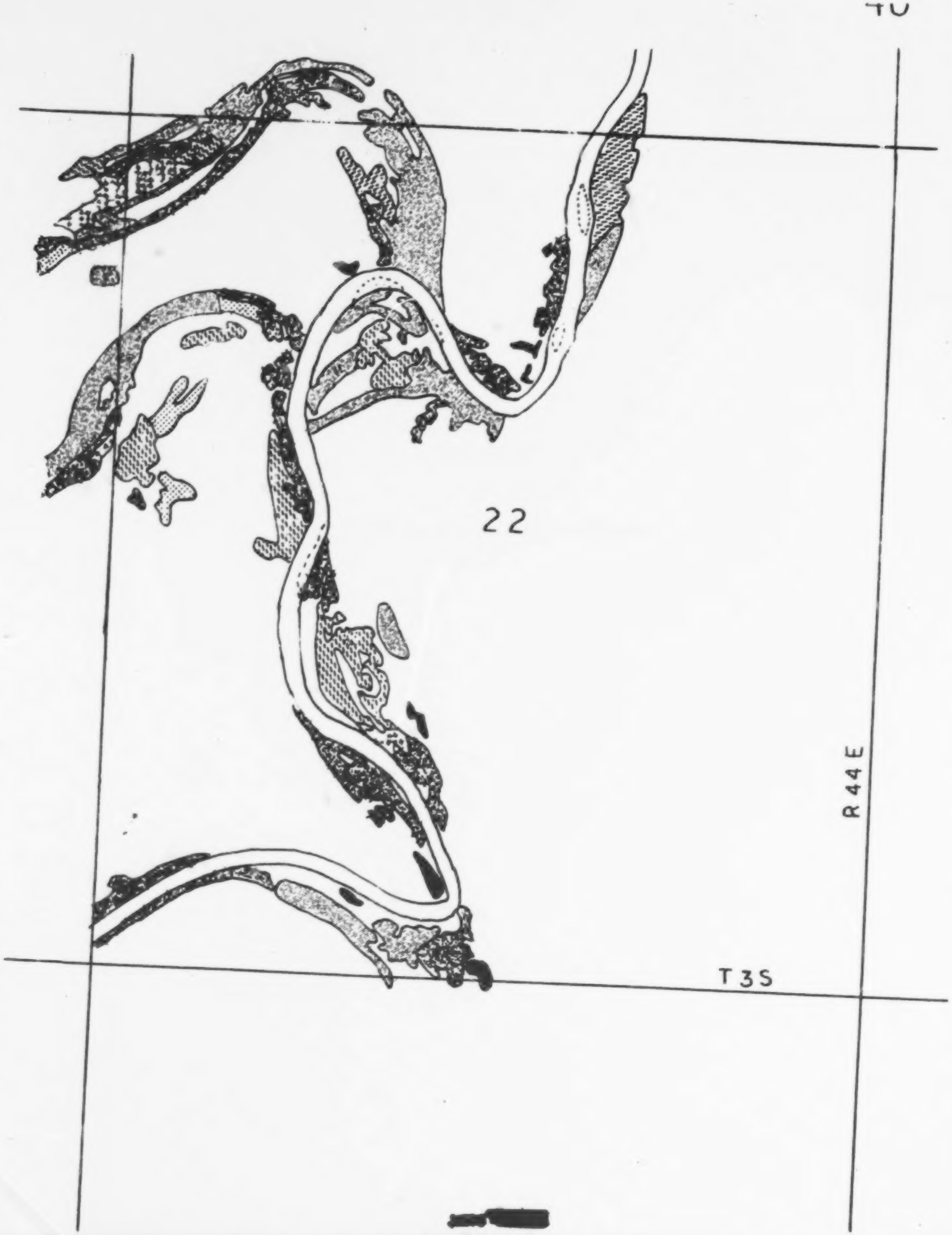
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22
R 44 E
T 3 S

APPENDIX K

SEDIMENT-DISCHARGE RATING CURVES

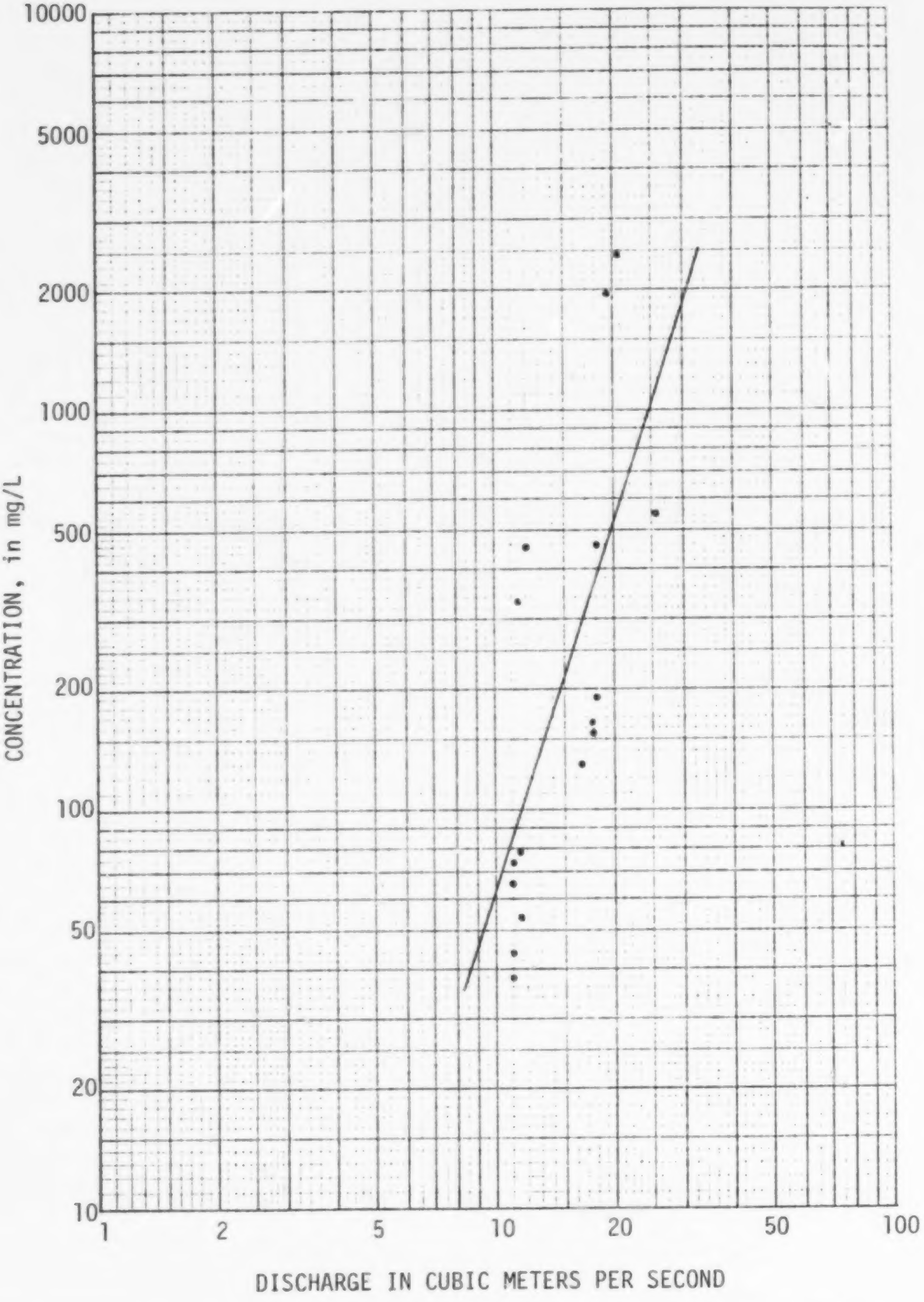

Figure K-1: Total Suspended Sediment Concentration Curve for the Ft. Keogh Section, Tongue River, Montana.

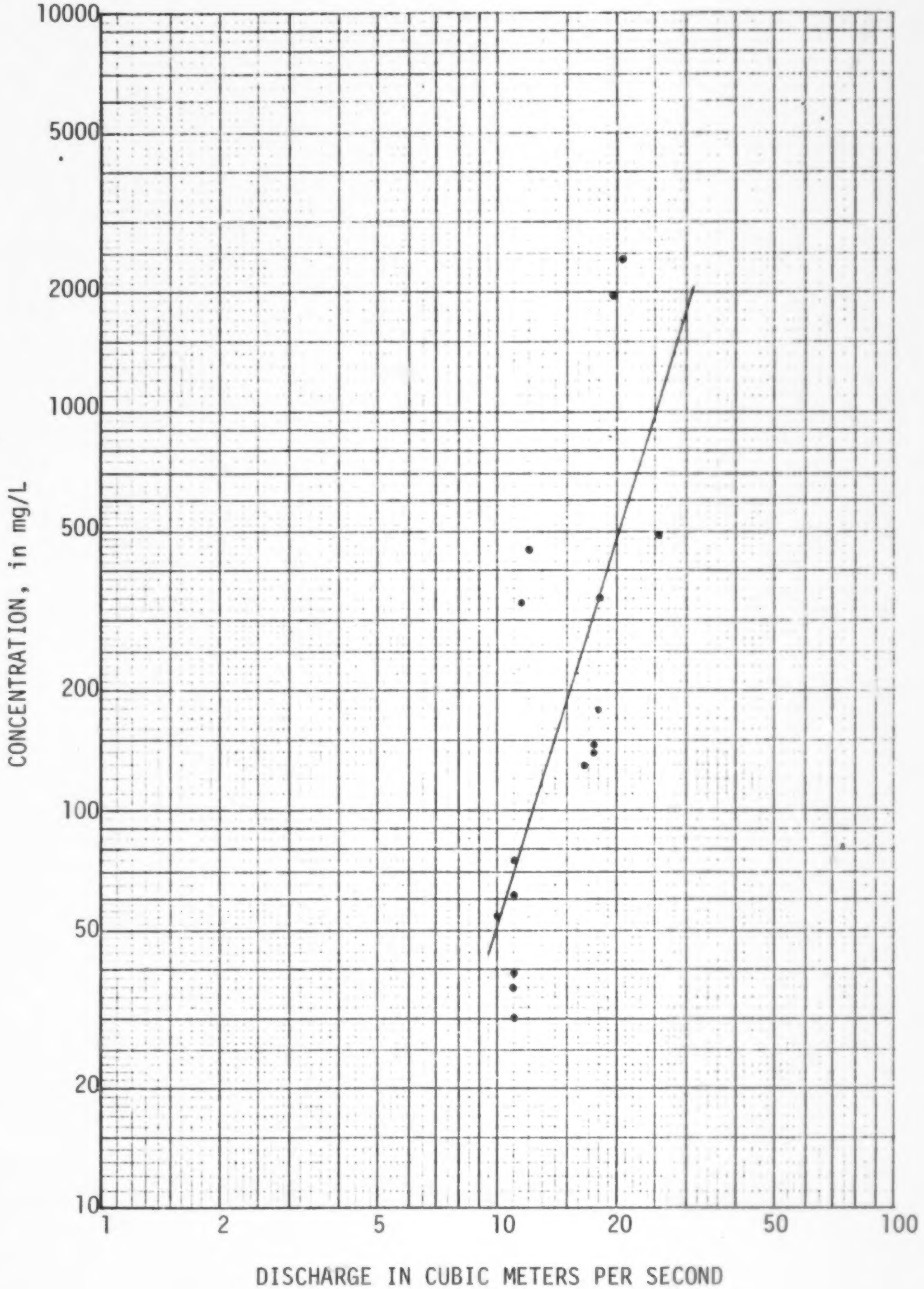

Figure K-2: Concentration of Particles Smaller than 62 Microns (Silt-Clay Fraction) as Suspended Load, Ft. Keogh Section, Tongue River, Montana.

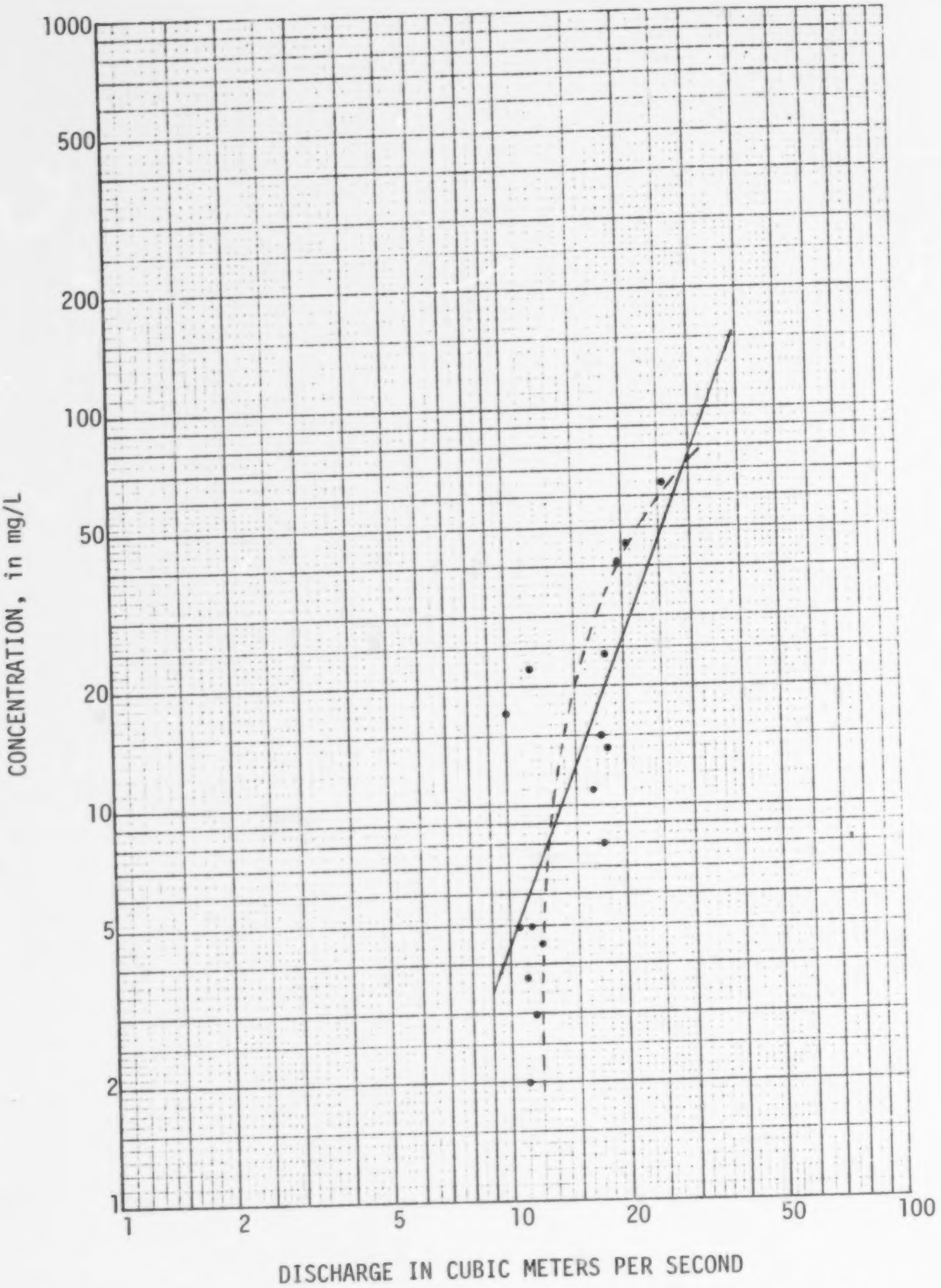

Figure K-3: Concentration of Particles Larger than 62 Microns (Sand Fraction) as Suspended Load, Ft. Keogh Section, Tongue River, Montana.

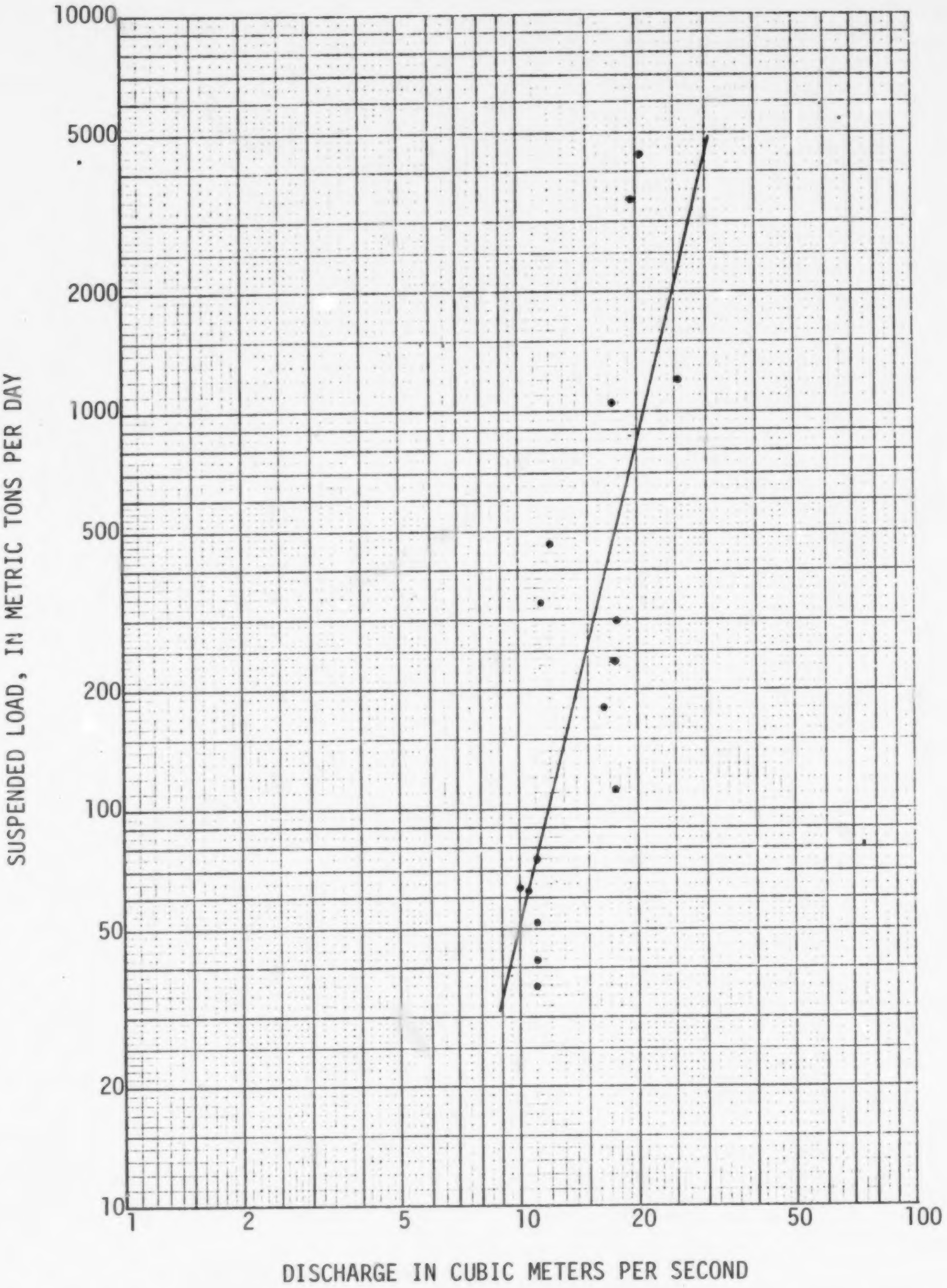

Figure K-4: Total Suspended Sediment Load Curve for the Ft. Keogh Section, Tongue River, Montana.

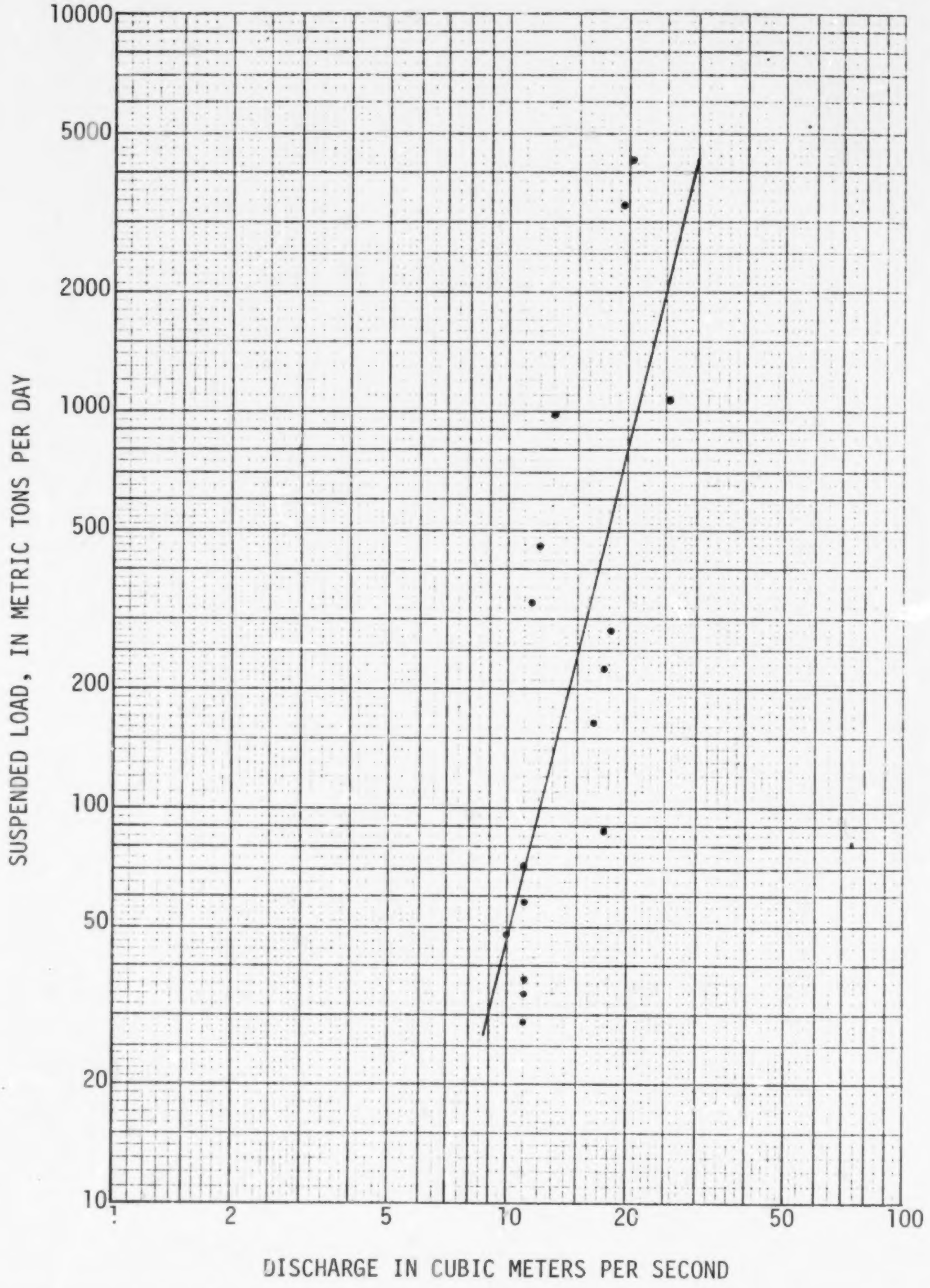

Figure K-5: Total Suspended Load Curve for Particles Smaller than 62 Microns (Silt-Clay Fraction) for the Ft. Keogh Section, Tongue River, Montana.

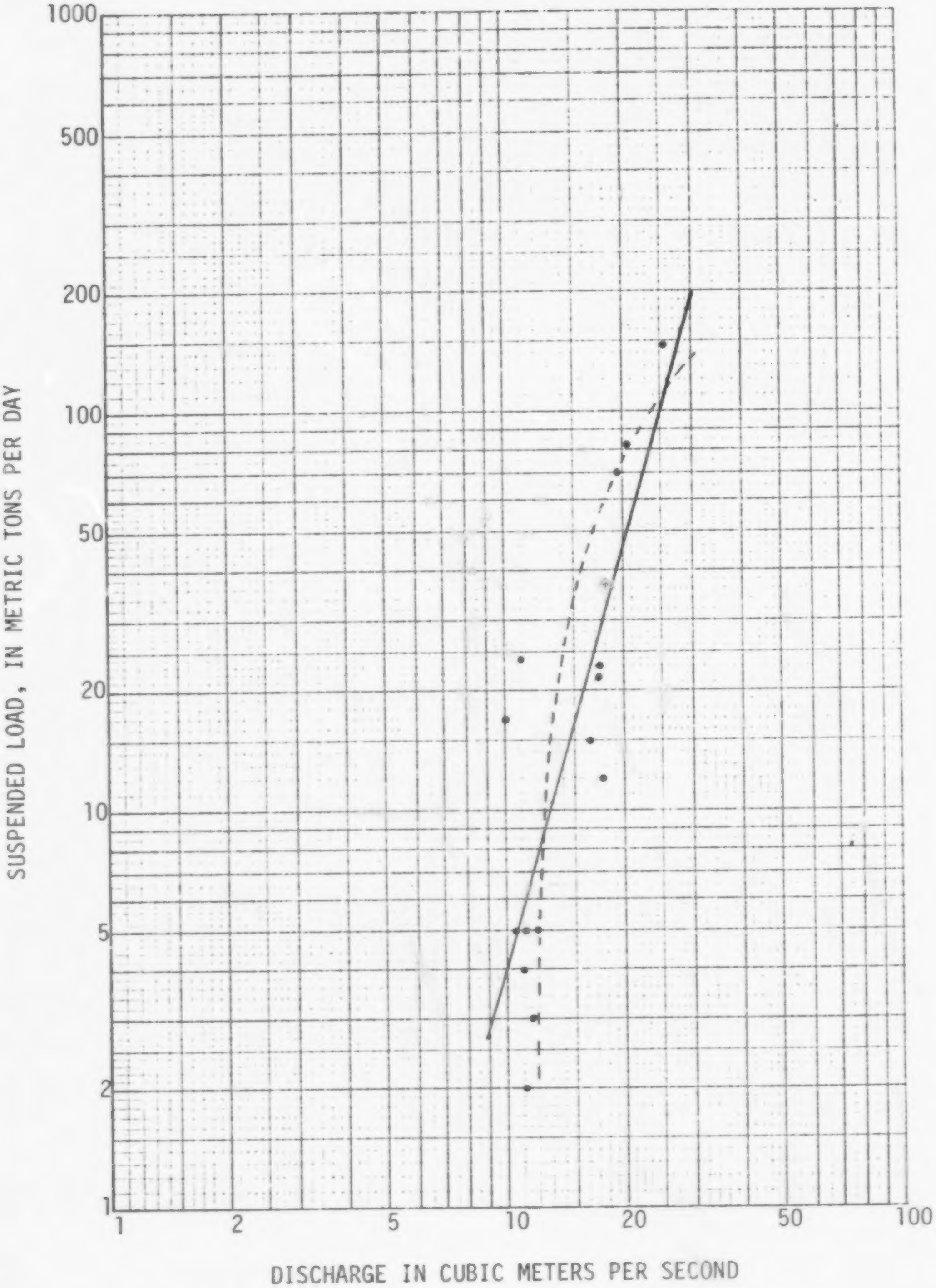

Figure K-6: Suspended Load Curve for Particles Larger than 62 Microns (Sand Fraction) for the Ft. Keogh Section, Tongue River, Montana.

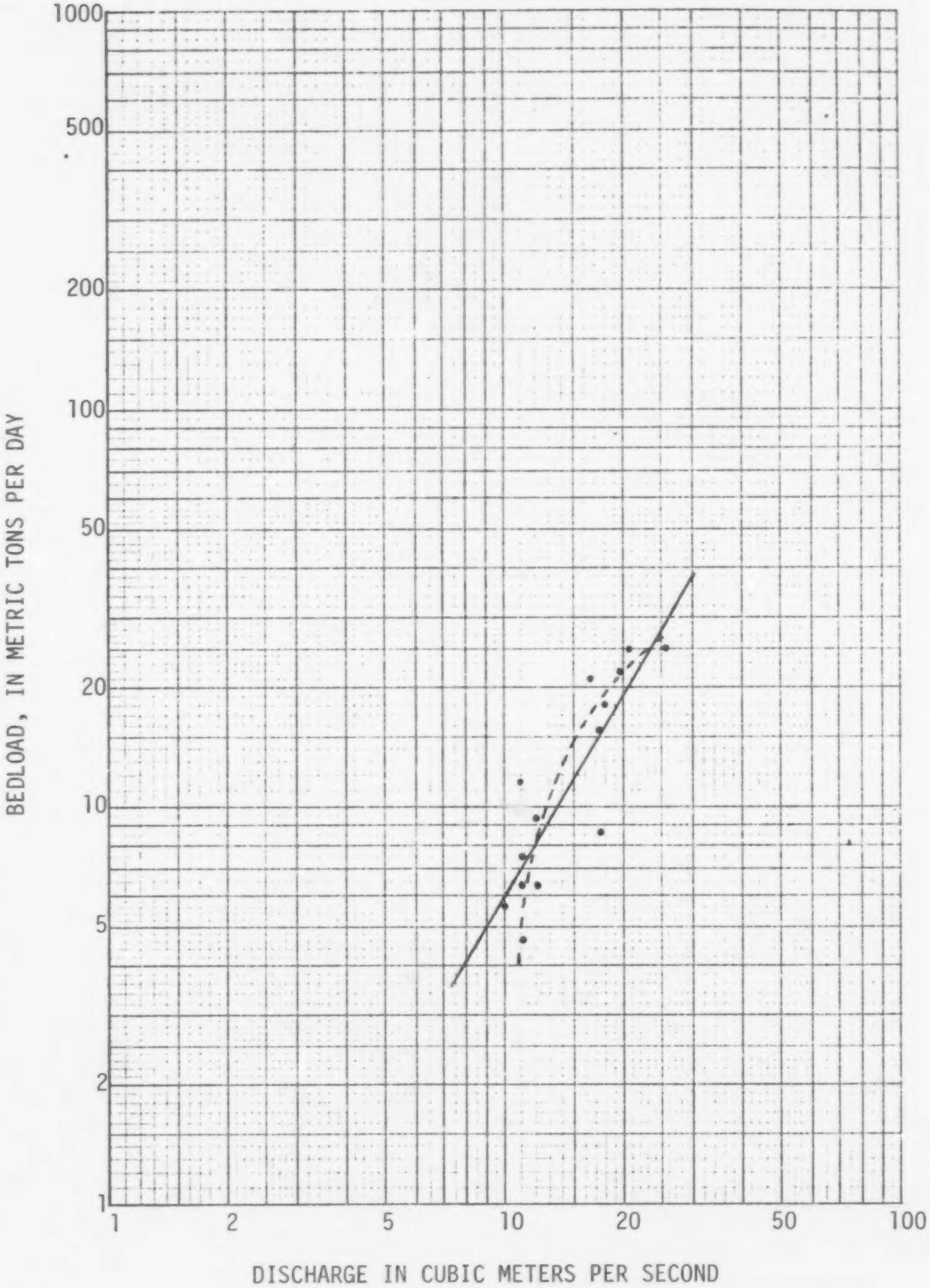

Figure K-7: Total Sediment Bedload Curve for the Ft. Keogh Section, Tongue River, Montana.

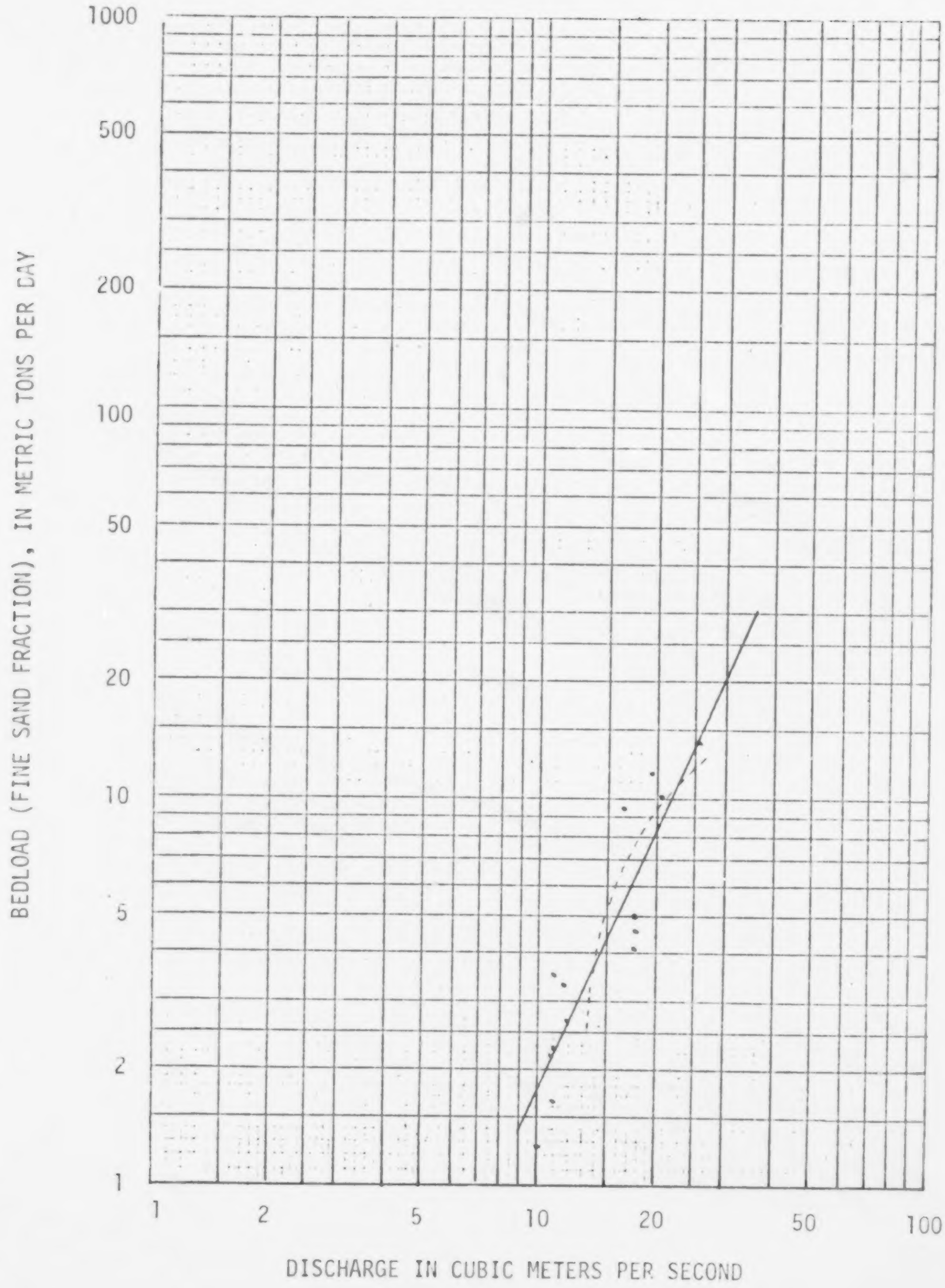

Figure K-8 : Movement of Fine Sand (125 to 250 Microns) as Bedload in the Ft. Keogh Section, Tongue River, Montana

[redacted]

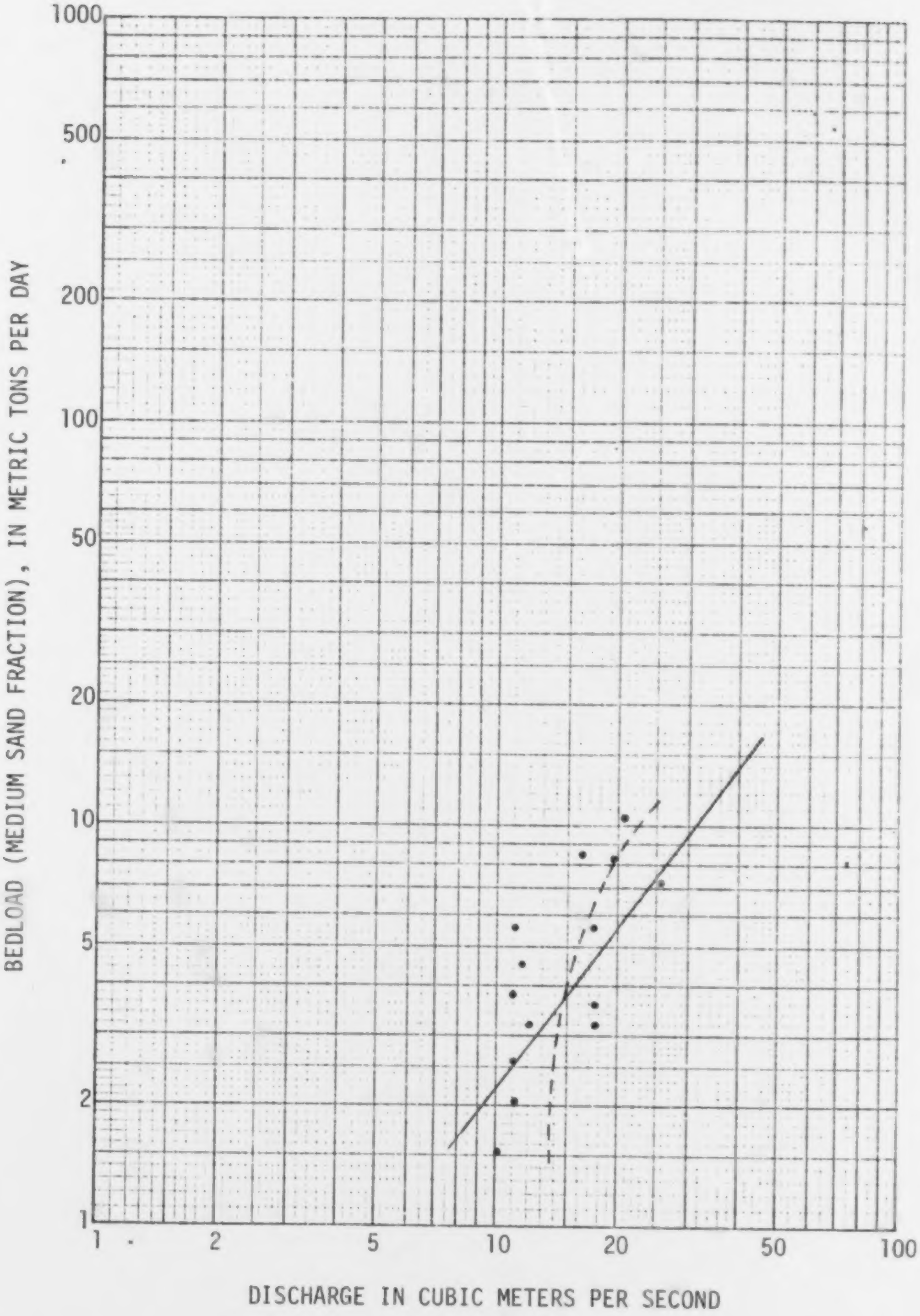

Figure K-9: Movement of Medium Sand (250 to 500 Microns) as Bedload in the Ft. Keogh Section, Tongue River, Montana.

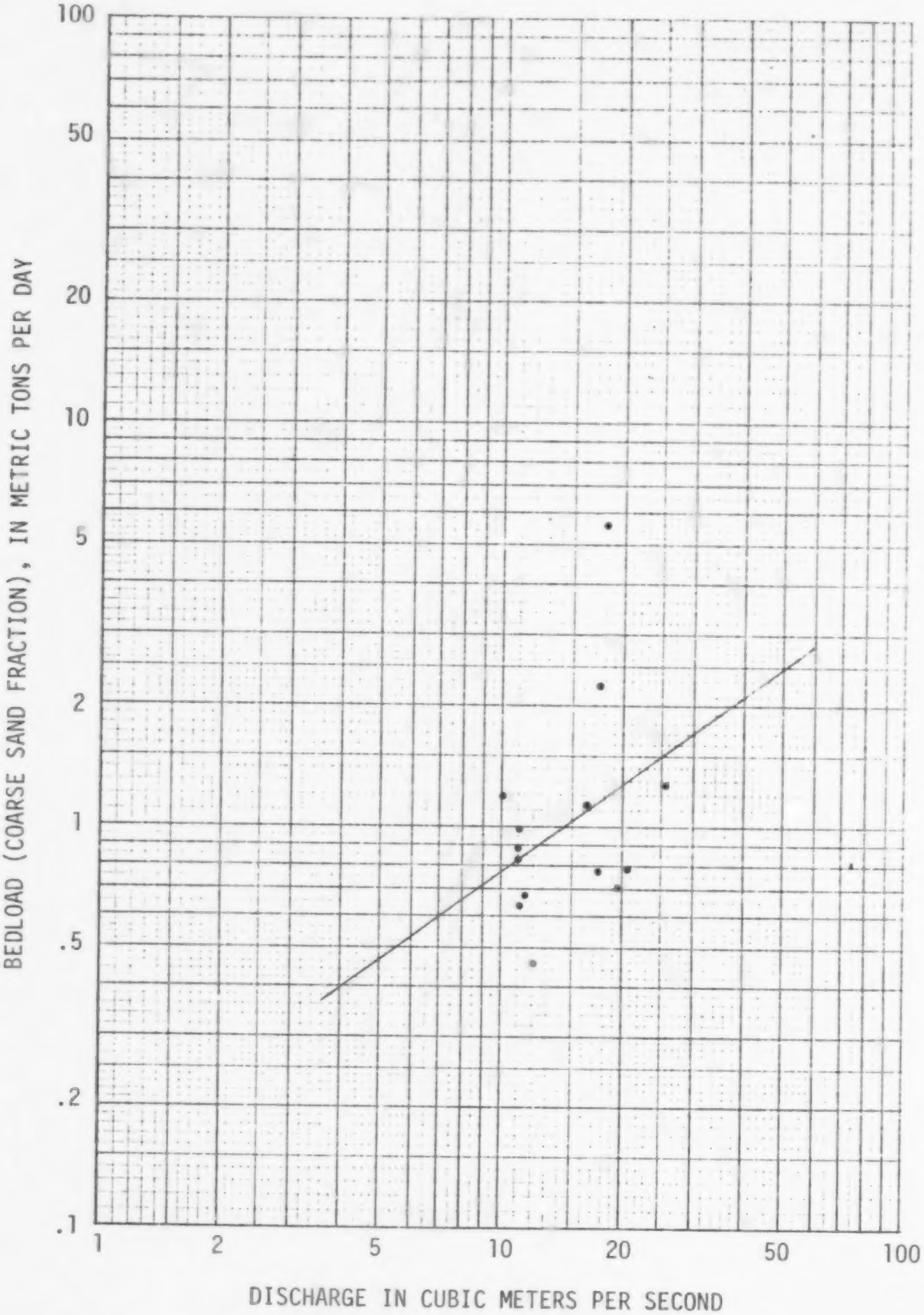

Figure K-10: Movement of Coarse Sand (500 to 1000 Microns) as Bedload in the Ft. Keogh Section, Tongue River, Montana.

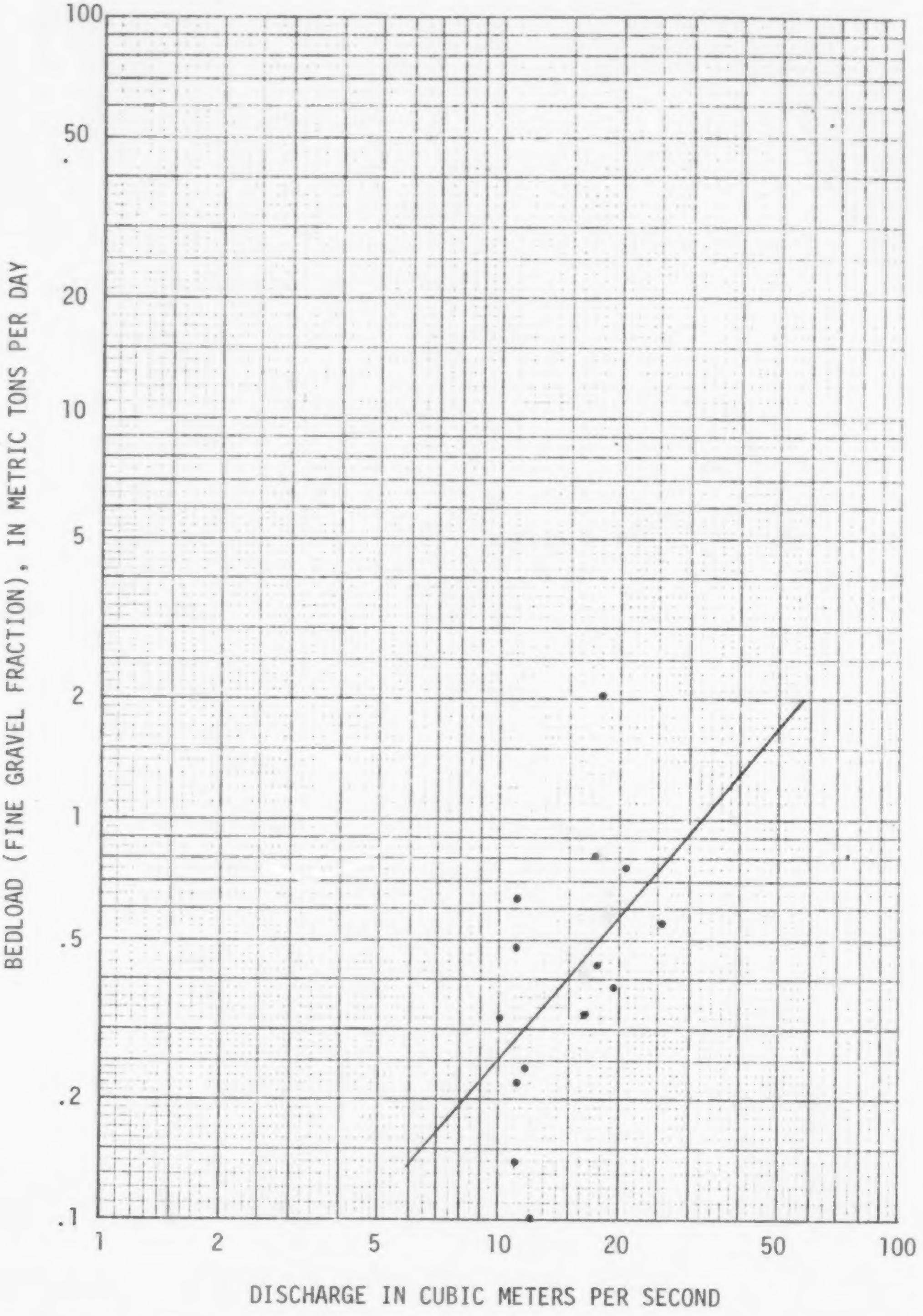

Figure K-11: Movement of Fine Gravel (1 to 2 mm) as Bedload in the Ft. Keogh Section, Tongue River, Montana.

[redacted]

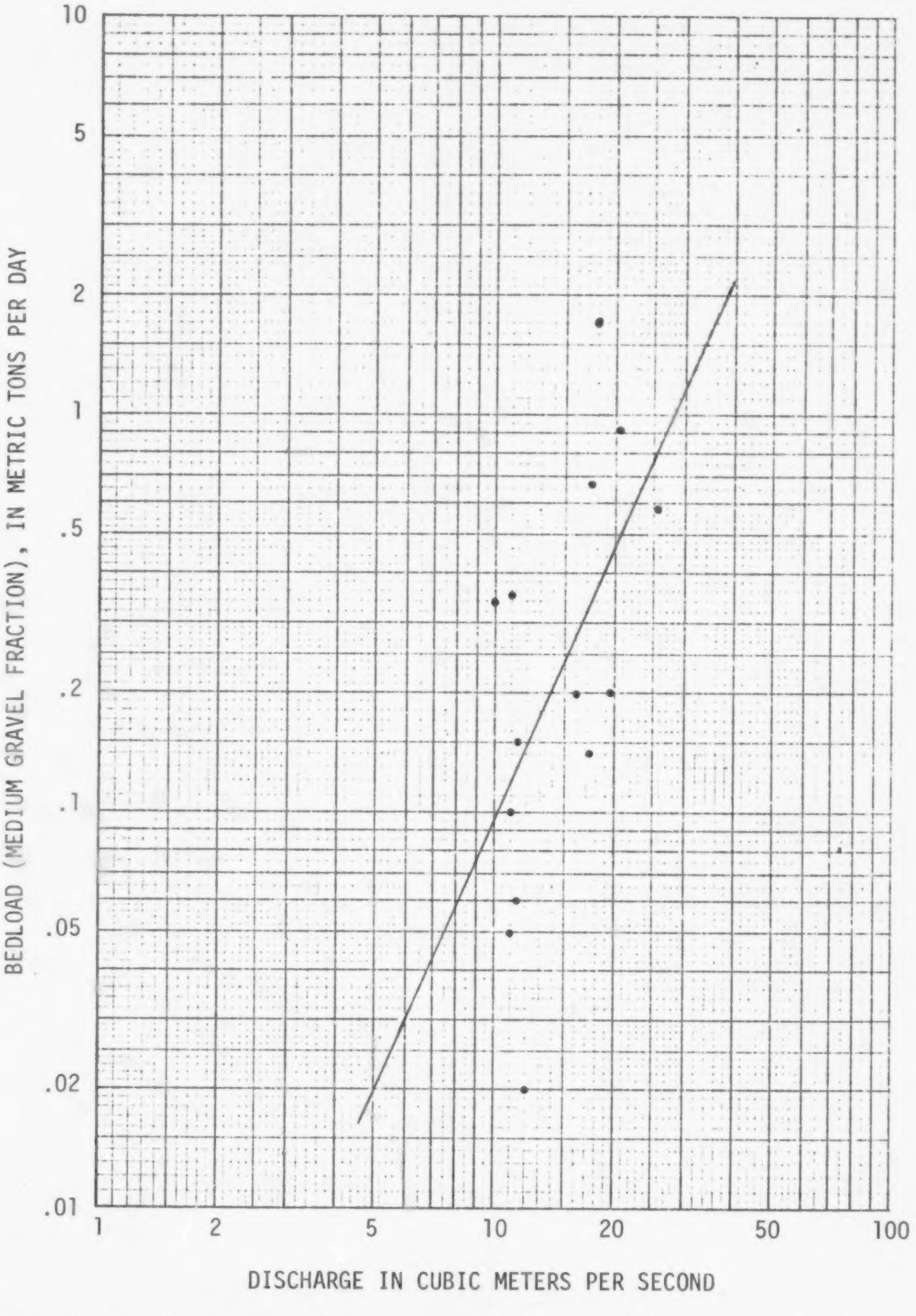

Figure K-12: Movement of Medium Gravel (2 to 4 mm) as Bedload in the Ft. Keogh Section, Tongue River, Montana.

[redacted] [redacted]

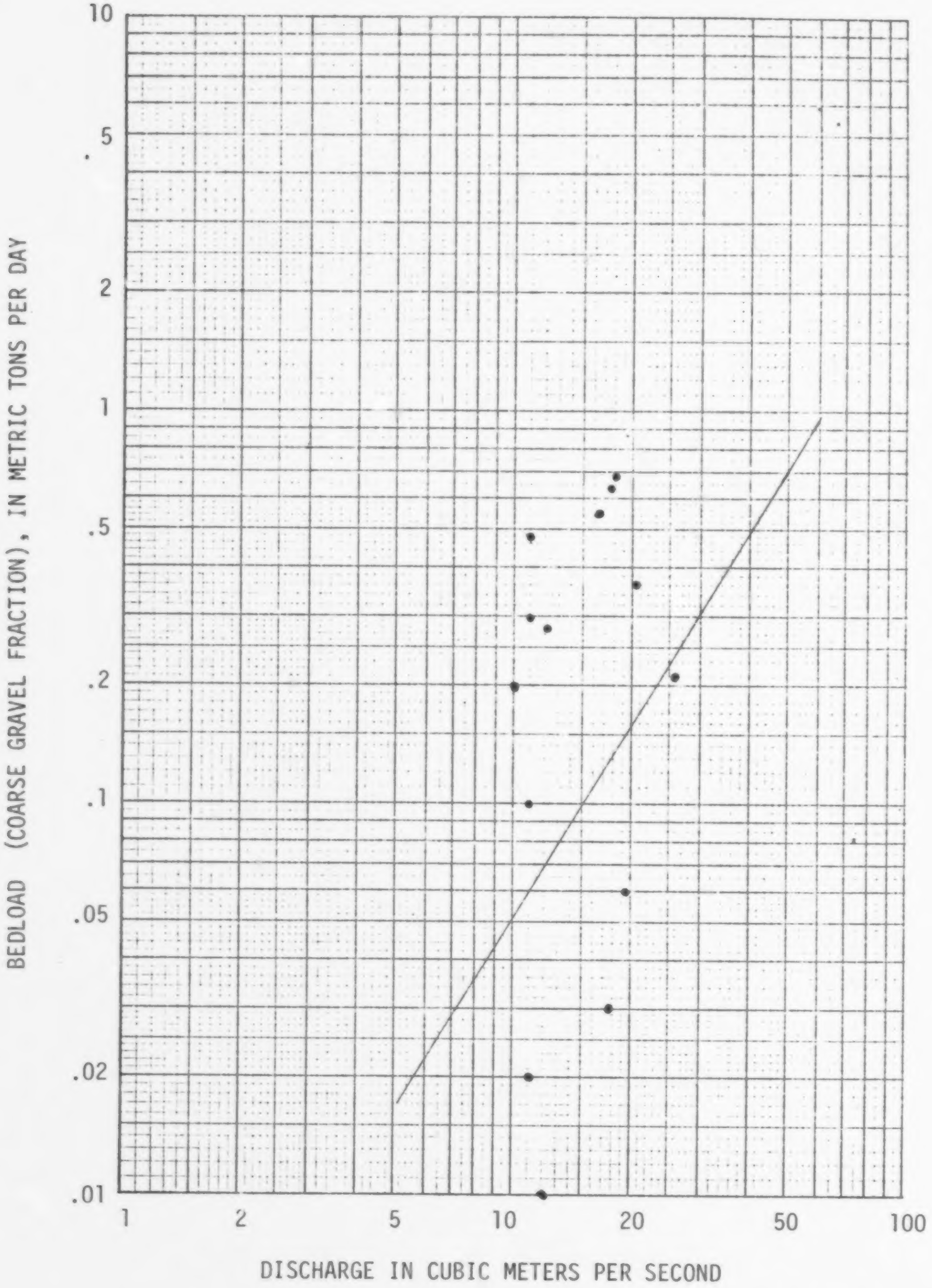

Figure K-13: Movement of Coarse Gravel (4 to 8 mm) as Bedload in the Ft. Keogh Section, Tongue River, Montana.